MONTHLY WEATHER REVIEW

VOLUME 79 NUMBER 6

JUNE 1951

CONTENTS

U. S. DEPARTMENT OF COMMERCE · WEATHER BUREAU

DEPARTMENT OF COMMERCE
CHARLES SAWYER, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

Editor, JAMES E. CASKEY, JR.

Volume 79
Number 6

JUNE 1951

Closed August 15, 1951
Issued September 15, 1951

FORECASTING THE FORMATION AND MOVEMENT OF THE CEDAR KEYS HURRICANE, SEPTEMBER 1–7, 1950[1]

ROBERT C. GENTRY

Weather Bureau Office, Miami, Fla.

[Manuscript received February 16, 1951]

ABSTRACT

The Cedar Keys hurricane of September 1–7, 1950, formed south of Cuba and crossed the west coast of Florida near Cedar Keys. Thus its entire life was spent in an area where considerable upper air data were available, and during September 3–6 it was tracked almost constantly by either airborne or land-based radar. Its path was extremely erratic. Analyses of surface and upper air data are used to explain the formation and various changes in rate and direction of movement of the storm, including two loops in its path. The concept of steering, as used in the Weather Bureau's Hurricane Warning Center at Miami, and other forecasting tools are discussed.

CONTENTS

INTRODUCTION

The Cedar Keys hurricane of September 1–7, 1950, was notable for its erratic course (fig. 1 A). It was first discovered by aerial reconnaissance south of the Isle of Pines during the afternoon of September 1. For 36 hours it moved northward at 3 to 4 m. p. h., then it suddenly started moving 22 to 23 m. p. h. in a direction between north and north-northeast. This rate continued for about 10 hours during which the course gradually changed to one between north and north-northwest. For the next 14 hours it moved toward the north-northwest at 12 to 13 m. p. h. Then just as suddenly as it had started moving, it became nearly stationary again for 14 hours while it moved slowly in a counterclockwise loop. After completing the loop, it moved at 7 m. p. h. toward the northeast. It continued this course for 12 hours and again became quasi-stationary while making another counter-clockwise loop. After completing this loop, it moved toward the south or south-southeast at 4 m. p. h. for 12 hours. Finally, it gradually curved toward the east and then the north to a track that was more conventional for hurricanes. Throughout its history, the storm continuously threatened Florida, and from 0700 EST, September 3 until it lost its hurricane force early September 6, hurricane winds were either affecting the Florida coast or were within about 60 miles of the coast.

Because of the storm's nearness to land, sufficient data were collected to plot its path in detail. Furthermore, the hurricane was within the network of the United States and Cuban upper air stations from the time it developed until it dissipated. Thus, considerable data are available for the study of this storm that is especially interesting because its erratic movements presented great problems to the forecasters.

This research was started in the hope that solutions to certain definite problems could be found: (1) Why did the hurricane form? (2) Why did the hurricane accelerate

[1] Paper presented at 108th National Meeting of the American Meteorological Society in Tallahassee, Fla., December 5–7, 1950.

960514—51——1

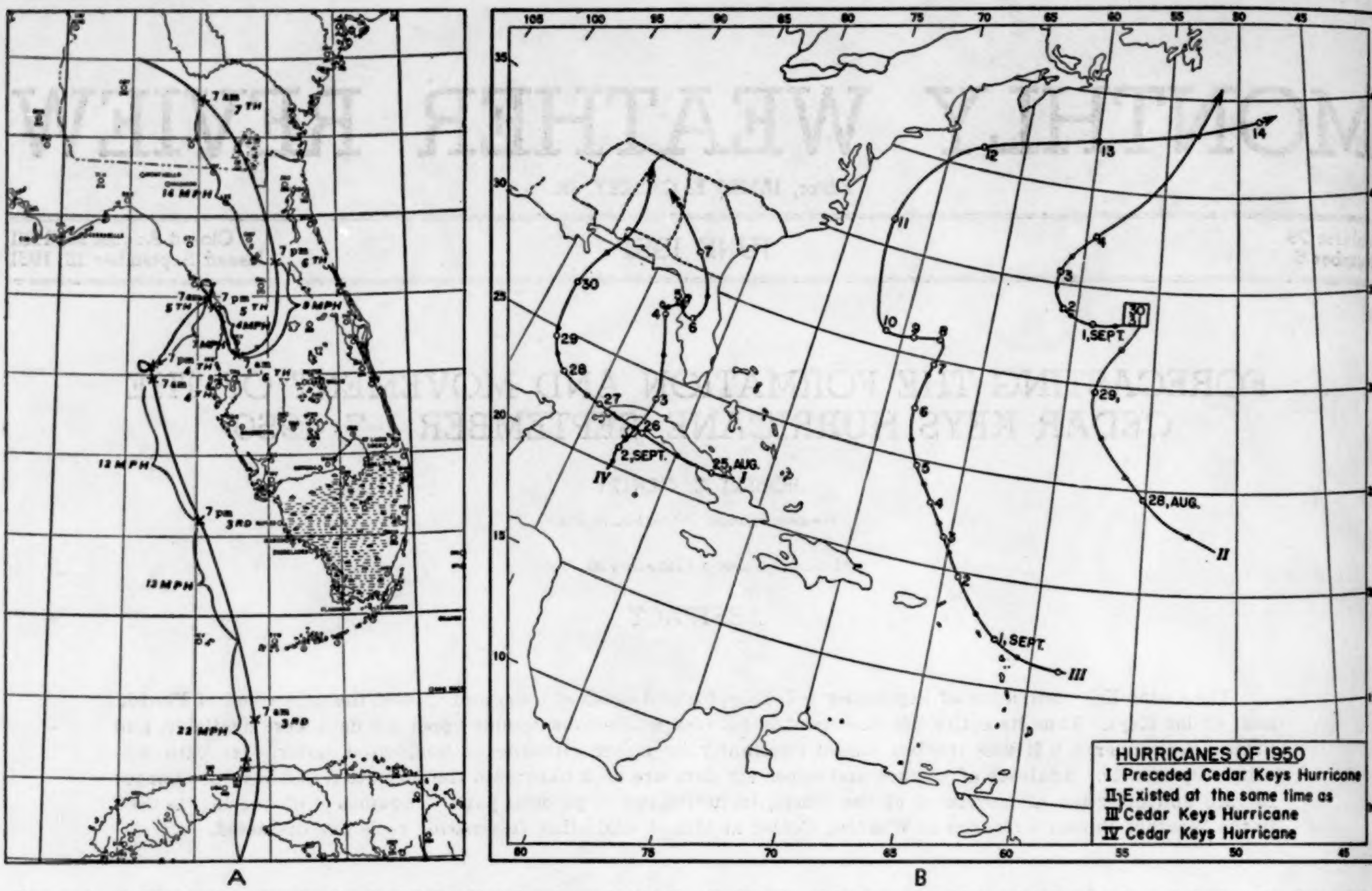


FIGURE 1.—A. Map section showing track of Cedar Keys hurricane in detail. B. Tracks of hurricanes which existed prior to and during the time of the Cedar Keys hurricane (IV). Open circles mark position of center at 0730 EST; solid circles, 1930 EST position.

so rapidly on the night of September 2–3? (3) Why did the hurricane move so slowly and make two loops on September 4–5? (4) How could the movement toward the south or south-southeast on September 5–6 have been forecasted? (5) What was the best available method for forecasting movements of this hurricane?

In studying the movement and formation of the hurricane, the following maps and charts were used: Sea level weather maps; constant pressure maps at 850 mb., 700 mb., 500 mb., and 300 mb.; pibal charts at selected levels from 2,000 feet to as high as the winds were reported; pseudo-adiabatic charts of the upper air soundings at Tampa, Miami, and Havana; time cross section for Tampa; and mean virtual temperature charts for the layer between 700 mb. and 500 mb. Most of the final conclusions were based on the constant pressure charts. Tracks on the 300-mb. charts give 12-hour positions of the height centers at that level. Tropical storm symbols on the constant pressure maps give the concurrent surface location of the storm's center.

FORMATION

On August 26 another hurricane had passed near the Isle of Pines moving from the east (fig. 1B). It crossed the western end of Cuba, intensified in the Gulf of Mexico, turned northward, and crossed the Gulf coast just east of Mobile. A trough of low pressure remained over the Western Caribbean after this earlier storm had passed into the Gulf, and the Cedar Keys hurricane formed in this trough. It was first located by aerial reconnaissance on the afternoon of September 1. However, rain had been very heavy over all of western Cuba and the waters between Swan Island and Cuba for 2 days previously, and a closed Low had developed in the levels near the surface.

On the night of August 31–September 1, the widespread heavy rain seemed to become concentrated in the area south of the Isles of Pines. By this time, the sea level pressure had fallen to 1,005 mb. (fig. 2) and possibly lower. Thus conditions were ripe for tropical storm development according to Riehl [1] if some mechanism were in the higher levels above the area of surface low pressure to remove some more air and cause deepening of the disturbance. Although upper air data are too sparse to make a quantitative analysis of divergence of the wind field at higher levels, data available indicate that horizontal divergence took place above the incipient center.

The equation for gradient winds on the rotating earth is

$$\frac{1}{\rho}\frac{dp}{dn}=fv\pm\frac{v^2}{r}$$

where ρ is density; p is pressure; n is distance measured normal to the isobars; f, the Coriolis parameter; v, the

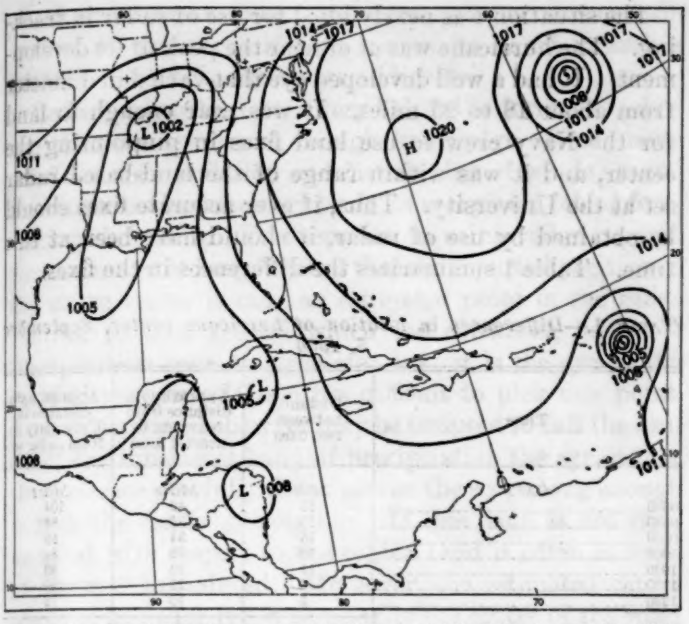


FIGURE 2.—Chart showing sea level isobars for 1930 EST, August 31, 1950.

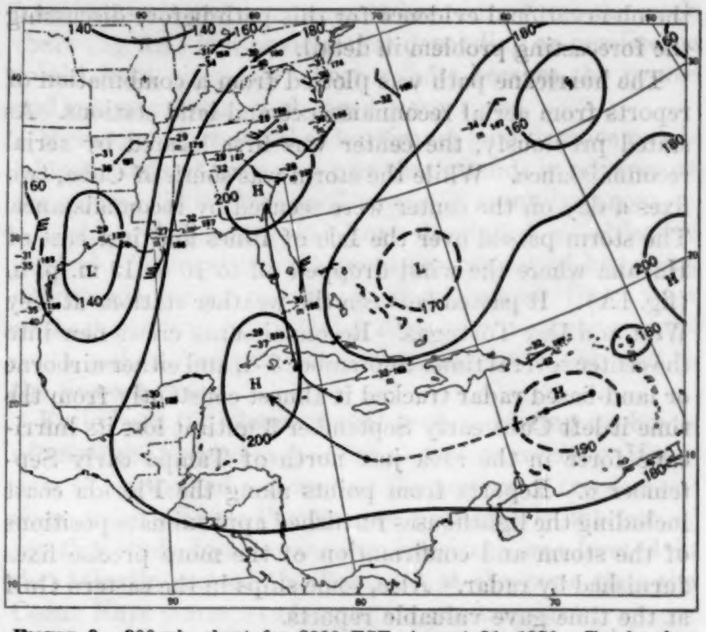


FIGURE 3.—300-mb. chart for 2200 EST, August 31, 1950. Tracks show 12-hour movement of Highs.

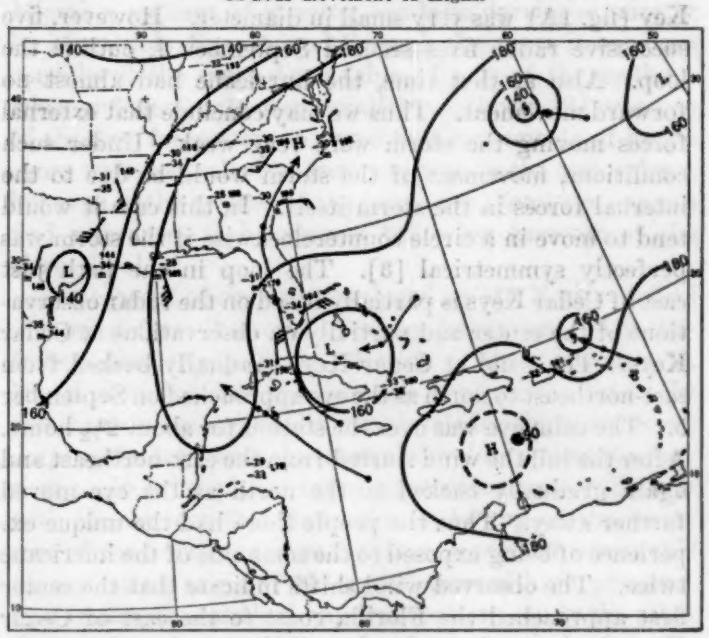


FIGURE 4.—300-mb. chart for 2200 EST, September 1, 1950. Tracks show 12-hour movement of Highs and Lows.

wind velocity; and r, the radius of curvature of the particle path. The positive sign is used for cyclonic paths and the negative sign for anticyclonic paths. Thus in steady flow the force due to the pressure gradient is balanced by the deflecting forces and the wind flows parallel to the isobars or contours. However, if the pressure gradient is increased, the terms on the right no longer balance it; for due to the conservation of momentum, air particles may not assume immediately the velocity called for by a changed pressure gradient. Since the deflective forces vary with the velocity, they will not balance the pressure gradient force until the wind is steady again.

Tracks on maps of 2200 EST August 31 (fig. 3), and 2200 EST September 1 (fig. 4) show that at 300 mb. a high pressure system moved over the developing storm on the night of August 31, and stayed in that vicinity for about 24 hours before resuming its northwestward course. At the same time cyclogenesis occurred in the trough to the east. Stagnation of the High and deepening of the trough resulted in increased pressure gradient and accelerating winds at 300 mb. above and east of the storm, e. g., the winds at Miami and Havana accelerated considerably at 300 mb. and higher levels. So long as the winds were sub-gradient, there would be horizontal divergence over the developing center, for the pressure gradient force would be larger than the deflecting forces in our equation. Since the pressure force is directed toward low pressure (to the left when looking downstream), this would cause a net movement of air from high toward low pressure. That is, it would cause air at 300-mb. and higher levels to move from the High above the developing storm center toward the low pressure trough to the east.

Once the storm had started there was plenty of energy available to keep it going and to cause intensification. Palmén [2] has explained that once a hurricane is formed, its solenoidal field is such that it will maintain itself as long as the air feeding into it near the surface is warm and moist and there is not too much surface friction. The air south of Cuba on September 1 met all specifications.

OBSERVED MOVEMENT

Once the storm had formed, the next problem was to predict its course and rate of movement. The difficulty of doing this has already been suggested by the erratic course shown in figure 1A, and it is of interest to evaluate

the observational evidence for this path before discussing the forecasting problem in detail.

The hurricane path was plotted from a combination of reports from aerial reconnaissance and land stations. As stated previously, the center was first located by aerial reconnaissance. While the storm was south of Cuba, two fixes a day on the center were secured by reconnaissance. The storm passed over the Isle of Pines and just east of Havana where the wind dropped off to 10 or 15 m. p. h. (fig. 1A). It passed between the weather stations at Key West and Dry Tortugas. Reconnaissance crews flew into the center several times September 3–4, and either airborne or land-based radar tracked it almost constantly from the time it left Cuba early September 3 until it lost its hurricane force in the area just north of Tampa early September 6. Reports from points along the Florida coast including the lighthouses furnished approximate positions of the storm and confirmation of the more precise fixes furnished by radar. Also, some ships in the eastern Gulf at the time gave valuable reports.

The loop in the path when the center was west of Anclote Key (fig. 1A) was very small in diameter. However, five successive radar fixes secured September 4, outline the loop. Also at that time, the hurricane had almost no forward movement. Thus we may conclude that external forces moving the storm were very weak. Under such conditions, movement of the storm would be due to the internal forces in the storm itself. In this case it would tend to move in a circle counterclockwise if the storm was perfectly symmetrical [3]. The loop in the path just east of Cedar Keys is partially based on the radar observations of the center and partially on observations at Cedar Keys. The wind at Cedar Keys gradually backed from east-northeast to north as the eye approached on September 5. The calm eye was over the station for about 2½ hours. After the lull the wind started from the east-northeast and again gradually backed to the north as the eye moved farther away. Thus the people there had the unique experience of being exposed to the same side of the hurricane twice. The observed wind shifts indicate that the center first approached the Florida coast to the east of Cedar Keys then moved westward until the western edge of the eye was over the station. When the storm started moving again, it was toward the east or southeast and thus a loop to the east of Cedar Keys was completed.

As the storm approached the coastline, it was tracked by two radar observers. One was at the University of Florida at Gainesville, the other was airborne in a Navy plane. Seven fixes furnished the Hurricane Central at Miami from the Navy plane coincided in time with fixes furnished by the University of Florida. Although it is impossible to say which of the two groups of fixes is more nearly correct, we can obtain some idea of the accuracy of the fixes by comparing them. They were obtained by two different crews, using two different radars, and working entirely independently of each other.

The situation was nearly ideal for use of radar in tracking. The hurricane was at or near the peak of its development. It had a well developed eye that varied in diameter from about 18 to 25 miles. It was near enough to land for the Navy crew to use land fixes in pinpointing the center, and it was within range of the land-based radar set at the University. Thus, if ever accurate fixes should be obtained by use of radar, it should have been at this time. Table 1 summarizes the differences in the fixes.

TABLE 1.—*Differences in location of hurricane center, September 5, 1950*

Time	Distance between two fixes	Approximate distance from Navy fix to nearest land	Approximate distance of University fix from radar set
GMT	*Miles*	*Miles*	*Miles*
0630	10	42	104
0830	10	35	88
0900	13	34	88
1000	10	30	84
1030	11	28	83
1130	5	21	80
1230	5	10	73
Average	9.1		

If we assume that either of the crews made absolutely accurate fixes, the errors made by the other group varied from 5 to 13 miles. If we assume that the true position of the hurricane was half way between the corresponding fixes, the average error was 4.6 miles. This is certainly acceptable from the standpoint of accuracy.

In earlier days, forecasters ordinarily used fixes at least 12 hours apart in calculating direction and rate of movement of hurricanes. While that may not be necessary now with the more complete data that are available, a smoothed path such as that given by the 12-hour fixes is still best in computing long-period direction and rate of movement. Short-period fluctuations in direction and rate of movement of the hurricane's center as determined from fixes by the two radars are illustrated by table 2.

From 1000 GMT to 1130 GMT the University of Florida reports indicated that the hurricane was moving at 3 m. p. h. in a direction of 40°, and the Navy radar reports indicated that the hurricane was moving at 8 m. p. h. in a direction of 80°. It is not within the scope of this report to determine the sources of error leading to these conflicting indications, but it is obvious that even though individual fixes on the center are relatively accurate, two succes-

TABLE 2.—*Direction and rate of movement of hurricane*

Time (GMT)	Movement indicated by fixes from University of Florida		Movement indicated by fixes from Navy radar plane	
	Direction (degrees)	Speed (m. p. h.)	Direction (degrees)	Speed (m. p. h.)
0630–0830	20	8	20	8
0830–1000	50	3	50	3
1000–1130	40	3	80	8
1130–1230	40	8	50	10
0630–1230	30	5	40	6
0245–1230			40	8
0245–0830			30	6

sive fixes taken too close together can give erroneous indications of movement if both happen to be off in such a manner as to make the errors additive.

Radar reports have been very helpful to forecasters during the past few years, though knowledge of maximum winds in the circulation and distribution of winds around the center is also necessary to do an acceptable job of forecasting the storm. Furthermore, in using radar reports, forecasters must keep in mind that the reported position of the storm center is only an estimated point in the radar rainfall pattern around which the spiralling bands of precipitation seem to circulate; i. e., it is the eye in the rainfall pattern. It is often difficult to pick this point. An inexperienced observer may be tempted to call the center of the innermost band of precipitation the eye, rather than to trace carefully the echoes on the scope long enough to pick the center of rotation. If this band is not symmetrical with respect to the center (and it often is not), an error is introduced. Moreover, the estimated center observed by radar is not necessarily the center of the wind field, nor the point of lowest pressure. Ordinarily, it is the same as the pressure center for all practical purposes, but in immature storms, dissipating storms, or storms that have had their lowest layers disturbed while passing over land, this center observed by radar may be vastly different from the pressure center. Ordinarily radar observers recognize such situations and so report in their remarks.

In the case under discussion, as the storm approached Cedar Keys, the eye was well defined and the center observed by radar should have corresponded very closely to the pressure center. The small differences between the two series of reports can be accounted for by human errors of observation and by mechanical errors of the two radar sets.

After the storm crossed the Florida coast, it was tracked by the radar crew at the University of Florida until it began to dissipate early September 6, north of Tampa. In addition, reports from the regular weather stations supplemented by reports from laymen over which the storm passed, enabled us to track it accurately through Florida.

FORECASTING THE MOVEMENT

METHODS OF FORECASTING

In next considering the problem of predicting the course and rate of movement of the Cedar Keys hurricane, it is well to recall that there are several methods used to predict the course of a hurricane. It is well known of course, that there is a tendency for hurricanes to recurve into any polar trough passing to the north if the trough extends far enough south. However, there may be some element controlling both the movement of the hurricane and the movement and location of the trough rather than the trough attracting the hurricane.

From the beginning forecasters have used persistence in making their forecasts. That is, they forecast what has been happening will continue to happen. From the track chart (fig. 1A) it is obvious that depending on persistence would have given very poor results because the course and rate of movement changed many times.

Simpson [4] argues that hurricanes tend to move parallel to the axis of the warm core that extends in advance of the storm. This gives good results in many instances.

Riehl and Burgner [5] have developed an objective method of forecasting the zonal component of hurricane movements using 5-day mean 700-mb. maps. Since most of the movements of the Cedar Keys hurricane were north-south rather than east-west, this method was not used in the present study.

Fujiwhara [6] observed that two co-existing typhoons often rotate around each other and more recently, Haurwitz [7] presented a theory on the motion of tropical cyclone pairs. These theories are particularly interesting for this study because another hurricane was located in the Atlantic east of the Bahamas at the same time the Cedar Keys storm was tracing its erratic course.

In the Weather Bureau's Hurricane Warning Center at Miami, a concept of steering has been developed, mostly by Mr. Grady Norton, and through the years it has been considered the most dependable of any of the methods when sufficient data were available. Bowie [8] was one of the first forecasters to argue that movements of hurricanes were controlled by currents high in the atmosphere, but even in the earliest of the hurricane literature, one can find references to hurricanes following currents at the cirrus level.

The concept of steering developed by Mr. Norton differs somewhat from that used by many forecasters. The difference lies largely in the selection of the steering level. Mr. Norton does not use the same level all the time. In fact, he may use several different levels for the same storm, varying the level with the stage of development of the hurricane. In principle, he argues that a hurricane will move with the current that flows across the top of the warm core of the hurricane or rather that it will cut across this current at an angle of 10° to 20° toward high pressure. In practice, this method requires that one study the pibal charts and select the lowest level where winds over the surface position of the hurricane are not in the circulation of the hurricane, i. e., the winds over the hurricane seem to fit into a smooth pattern with the winds upstream and downstream from the hurricane. For example, in figure 5 which gives upper winds from an earlier storm, winds at Hatteras are obviously affected by the circulation of the hurricane up to at least 30,000 feet. From data at Hatteras, Charleston, and other nearby stations, one can deduce that the winds over the storm are still in the hurricane's circulation as high as 35,000 feet. However, at 40,000 feet the flow appears to be relatively smooth over the top of the hurricane, and this should be selected as the steering level. The hurricane symbol gives the position of the hurricane at the time of the pibal observations,

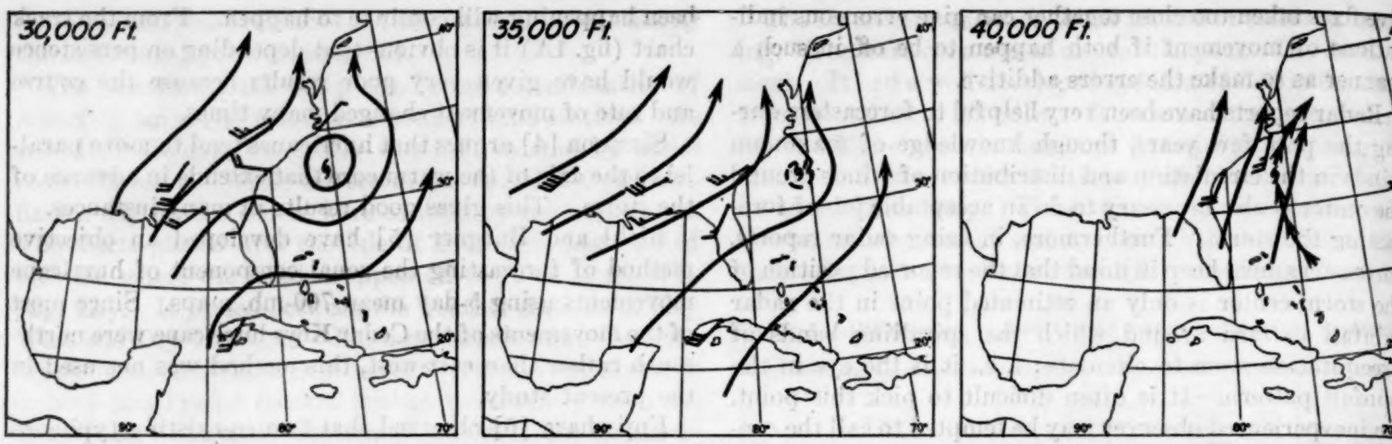


FIGURE 5.—Charts showing air flow over the southeast United States at 1600 EST, August 19, 1950, at (a) 30,000 feet, (b) 35,000 feet, and (c) 40,000 feet.

and the arrow gives the path of the hurricane before and after the pibals were taken. Using the concept of steering, forecasters were able to successfully predict that the center would pass to the east of Cape Hatteras. Previously, this concept of steering has given consistently good results when sufficient data were available for using it. Mr. Norton also believes that the rate of movement is highly correlated with the speed of the steering current. Qualitatively, this idea has been used and found correct, but unfortunately, there have never been sufficient data to check it quantitatively.

For some of the mature Cape Verde storms, the steering level is as high as 55,000 to 60,000 feet. Of course, data are seldom available to that height immediately over the storm. However, when pressure systems at the steering level are all large and streamlines relatively smooth, one can often deduce what the winds are over the storm from data at stations 500 to 1,000 miles away. However, when the flow at the steering level is broken up into several small vortices, it is very risky to make any deductions from data at long distances from the center. This was true of the Cedar Keys hurricane. Even a casual study of the 300-mb. maps in this series (figs. 3, 4, 6, 8, and 9) reveals that Highs and Lows in the vicinity of the hurricane were comparatively small in diameter.

In studying this storm, all of the forecasting methods were tried which were applicable to the situation. Since the high level steering concept gave best results, it is the only one that will be discussed.

APPLICATION OF THE STEERING CONCEPT

The first problem in forecasting the movement of the Cedar Keys hurricane was to account for the change on the night of September 2–3, when it accelerated from a forward speed of 5 or 6 m. p. h. to one of 22 or 23 m. p. h. At this stage of the storm development, one would have

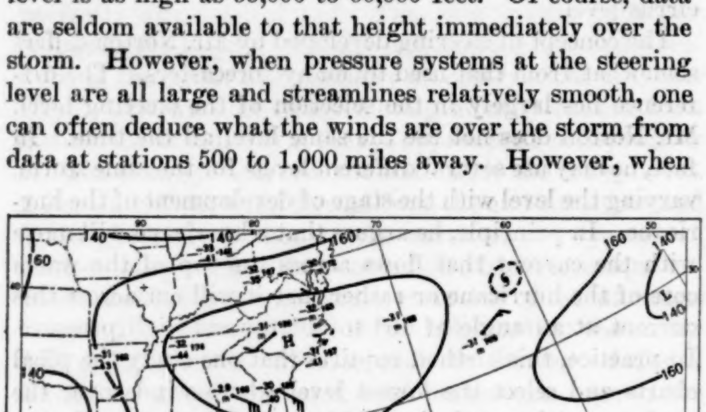


FIGURE 6.—300-mb. chart for 2200 EST, September 2, 1950. Tracks show 12-hour positions of Lows.

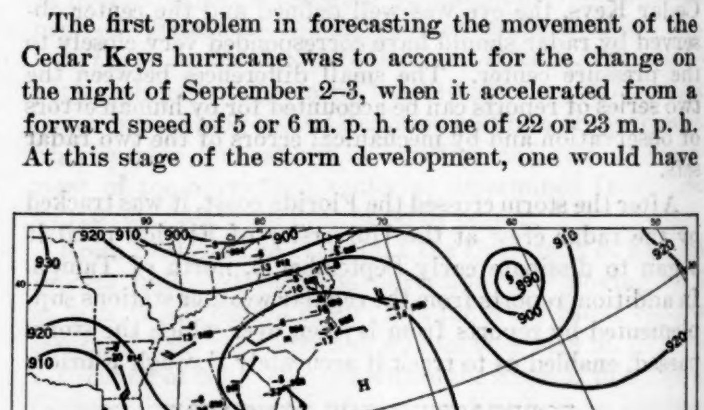


FIGURE 7.—500-mb. chart for 2200 EST, September 2, 1950.

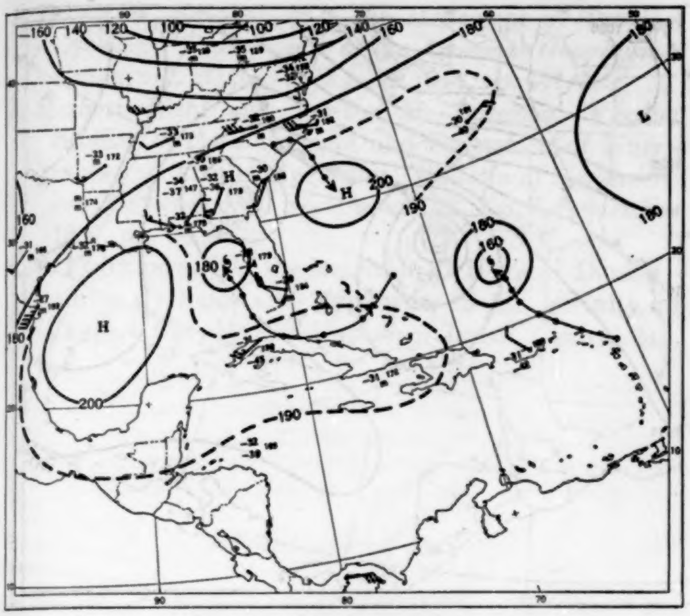


Figure 8.—300-mb. chart for 1000 EST, September 4, 1950. Tracks show 12-hour movement of Highs and Lows.

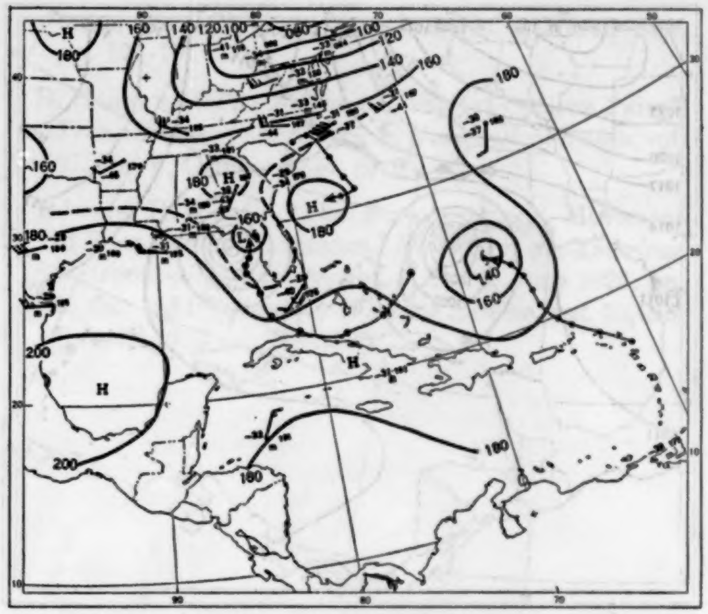


Figure 9.—300-mb. chart for 1000 EST, September 5, 1950. Tracks show 12-hour movement of Highs and Lows.

expected to find the steering level somewhere near 30,000 feet. The 30,000-foot winds at Havana at 2200 EST, September 2, (fig. 6) were taken at about the time of the acceleration and they were from a westerly direction and very weak—nothing there to indicate a sudden acceleration toward the north-northeast. However, at 300-mb. cyclogenesis had taken place east of Miami and by 2200 EST September 2, the resulting Low had moved to a position north-northwest of Havana. (See figs. 3, 4, and 6 and the tracks thereon.) Before 2200 EST the top of the circulation of the hurricane was apparently shortly above the 500-mb. level (fig. 7). However, at about this time the circulation of the Low at 300 mb. which had moved in from the east was nearly superimposed on the circulation of the hurricane. This 300-mb. Low was moving at about 15 m. p. h. and when it reached this position north-northwest of Havana, it recurved toward the north—following about the same path taken by the High that preceded it. (See track of High centered over North Carolina on 300-mb. map for 2200 EST, September 1, (fig. 4).) At 2200 EST, September 2, this 300-mb. Low was centered north of the hurricane, but it was close enough to join the circulation of the hurricane. However, because of its northward position, it made the vertical axis of the hurricane tilt toward the north an abnormal amount. The acceleration was probably due to the circulation of the storm being picked up by the circulation of the 300-mb. Low which was steered by some current quite a bit higher. Unfortunately, data from high levels were not secured, and the steering level for the 300-mb. Low cannot be located. The hurricane moved at the speed of the 300-mb. Low plus an additional speed required for the lower part of the hurricane to catch up with the upper part. Thus the surface center moved at about 23 m. p. h. until it caught the 300-mb. Low. The latter had been moving about 15 m. p. h. but it slowed down some when it recurved to the north. As soon as the surface center caught the 300-mb. Low, it slowed down to 12 to 13 m. p. h.

On September 4 the hurricane became quasi-stationary so far as forward movement was concerned and traced the first of the loops in its track. At this time, the hurricane and the 300-mb. Low were apparently just one Low, and the steering level was apparently somewhat above the 300-mb. level. Again winds at the higher levels were not available in sufficient quantity to pick a steering current. However, from the height distribution on the 300-mb. chart, one can deduce that the steering winds were very light, for gradients near the storm were weak, and the hurricane was located about midway between the High in the Gulf of Mexico and the High in the Atlantic east of Jacksonville (fig. 8). There is no obvious reason for thinking that either of these Highs would predominate over the other at the levels shortly above the 300-mb. surface. Thus one could not be sure from the steering that the storm would stay stationary, but there is no reason for expecting much movement.

During the night of September 4, the hurricane moved slowly toward the northeast and reached the Cedar Keys area about 0700 EST, September 5. The next question is, how would the storm move when it reached the Florida coast? Sufficient winds still were not available at higher levels to accurately determine the steering level. From the flatness of the gradient near the storm at the 300-mb. level at 1000 EST, September 5 (fig. 9), it could be concluded that the steering level was not far above it, and that any movement should be rather slow.

Winds were available at Miami for higher levels. Therefore, let us study the contours on the 300-mb. map and try to deduce what winds should appear at Miami at higher levels if the north-northwest current which was

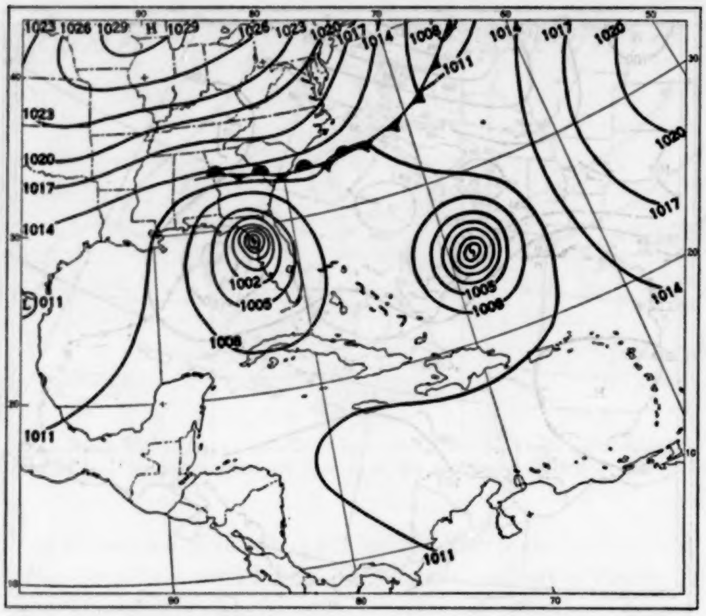


FIGURE 10.—Chart showing sea level isobars and fronts, 1330 EST, September 5, 1950.

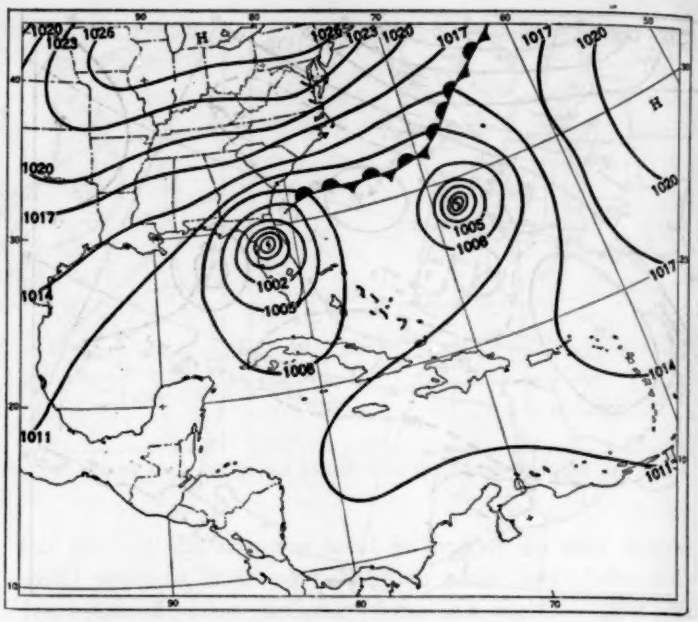


FIGURE 11.—Chart showing sea level isobars and fronts, 1330 EST, September 6, 1950.

west of the hurricane at the 300-mb. level were to appear farther east at the higher levels.

Let us assume for the sake of argument, that the entire contour pattern in the vicinity of Florida shifted farther east with height (fig. 9). Then, depending on how far east it shifted, the winds at Miami would be west, northwest, north, or possibly northeast if there were just a slight change in the shape of contours. Actually, at 35,000 feet, Miami had north winds of about 5 knots; and at 40,000 feet, had north winds of about 20 knots. This partially confirms that the steering current over the storm was from the northwest or north. Six hours later at 1600 EST while the hurricane was still moving toward the south-southeast, Valparaiso, Fla., which was west-northwest of the hurricane, reported north-northeast winds of about 20 knots. Thus all data available tend to confirm that at higher levels the flow over the hurricane was from a direction between northwest and northeast. Therefore, we can decide that the hurricane was still being steered by winds flowing over the top of the warm core. However, for this particular storm, with so many small vortices in the vicinity and with the usual scarcity of data at the higher levels, it was particularly difficult to locate the steering level and to ascertain the direction of the steering current.

At the time the hurricane became quasi-stationary near Cedar Keys, there was a large sea level high pressure system centered over Lake Michigan and its circulation extended far enough south to make contact with the outer circulation of the hurricane (fig. 10). It would have been simpler to have said that the High to the north blocked the advance of the hurricane. However, the circulation of the High never seemed to come in close contact with the stronger portion of the circulation around the hurricane. Furthermore, the High seemed to be more favorable to blocking the forward movement of the hurricane during the next day (fig. 11) when the storm was actually moving toward it than it did during the period when the storm was first quasi-stationary near Cedar Keys and then moved away from the High toward Tampa.

CONCLUSION

We have accounted for the development of the hurricane and have shown that high level steering could account for the various accelerations and changes in direction at all times when sufficient data were available. The acceleration on the night of September 2–3 could be accounted for by the movement of the warm core Low at 300 mb. and the effort of nature to return the inclination of the hurricane's axis to the vertical.

ACKNOWLEDGMENT

The author wishes to thank Mr. Grady Norton for his advice and encouragement, the staff of the Miami Weather Bureau for assistance in preparing the manuscript and illustrations, and the University of Florida and the U. S. Navy for use of their radar observations.

REFERENCES

1. Herbert Riehl, "A Model of Hurricane Formation," *Journal of Applied Physics*, vol. 21, No. 9, September 1950, pp. 917–925.
2. E. Palmén, "On the Formation and Structure of Tropical Hurricanes," *Geophysica*, Finland, No. 3, 1948, pp. 26–38.
3. Tu Cheng Yeh, "The Motion of Tropical Storms Under the Influence of a Superimposed Southerly Current," *Journal of Meterology*, vol. 7, No. 2, April 1950, pp. 108–113.

4. Robert H. Simpson, "On the Movement of Tropical Cyclones," *Transactions of the American Geophysical Union*, vol. 27, No. V, October 1946, pp. 641–655.

5. Herbert Riehl and Newton M. Burgner, "Further Studies of the Movement and Formation of Hurricanes and Their Forecasting," *Bulletin of the American Meteorological Society*, vol. 31, No. 7, September 1950, pp. 244–253.

6. S. Fujiwhara, "On the Behavior of Lines of Discontinuity, Cyclones and Typhoons, in the Vicinity of Japan," *Geophysical Magazine*, Japan, Central Meteorological Observatory, vol. 2, No. 2, March 1929, pp. 120–131.

7. B. Haurwitz, "The Motion of Tropical Cyclone Pairs," *Transactions of the American Geophysical Union*, vol. 27, No. V, October 1946, p. 658.

8. Edward H. Bowie, "The Formation and Movement of West Indian Hurricanes," *Bulletin of the American Meteorological Society*, vol. 3, No. 6, June 1922, pp. 95–96. (Also *Monthly Weather Review*, vol. 50, No. 4, April 1922, pp. 173–179.)

A METHOD OF FORECASTING PRECIPITATION 28-40 HOURS IN ADVANCE DURING OCTOBER

REINHART C. SCHMIDT

U. S. Weather Bureau, Washington National Airport, Washington, D. C.

Manuscript Received January 10, 1951]

ABSTRACT

A method is developed and described for forecasting whether measurable precipitation will occur at Washington, D. C., during the daylight hours "tomorrow" using meteorological information which is available to the forecaster during the early morning hours "today," namely the upper air observations taken "yesterday." Methods which the author had previously developed for use during summer and winter months were found ineffective when applied to October data. In the present system the initial assumption is made that rain *will* occur during the specified period. Procedures are then applied for eliminating rain from the forecast. Unless a rule is found which states that rain will not occur, rain is forecast.

Results obtained when the system is applied to Baltimore, Md., and Richmond, Va., using the same variables as used for Washington, D. C., are also shown.

CONTENTS

INTRODUCTION

The research described in this report was initiated following several embarrassing forecast errors during the month of October 1949. Its over-all purpose is to provide a systematic means of preventing, if possible, the recurrence of similar errors. Although forecasters use many methods, which are usually much more complex than pure extrapolation, in forecasting of rainfall for periods 24 to 48 hours in advance, there is little that can be found by way of published material to show just what methods or tools are the most useful. This report is therefore an attempt to set down a method of forecasting to be used during the month of October for Washington, D. C., Baltimore, Md., and Richmond, Va.

It was found that methods used for forecasting summer precipitation [1] and winter precipitation [2] which involved similar time lags met with failure when applied to data for the month of October. However, this is not a surprising result since the broad scale circulation patterns are changing during autumn and do not fit well either the summer or winter normals but are more or less a combination of the two. Thus, shower type precipitation may be expected at times, and during other periods a more general type of precipitation in connection with coastal developments. Moreover, October normally is one of Washington's driest months with an average of 2.91 inches of rainfall as compared with 4.42 inches for August and 3.32 inches for January. It averages fewer days with measurable precipitation than any summer or winter month. However, monthly totals have been as much as 8.81 inches and the greatest 24-hour amount was 3.98 inches.

SELECTION OF PROBLEM AND DATA

Forecasts for "tomorrow" issued from the 0130 EST surface map of "today" are considered to be of major importance because of the widespread dissemination given to them and the large amount of operational planning based on the forecasts issued during the early morning. There are many operations contingent on "daytime" weather for tomorrow as well as today's weather. Thus one's reputation as a successful forecaster for any specific location depends a great deal on maintaining a good record in forecasting tomorrow's daytime weather. The problem selected for study is therefore the prediction of whether or not measurable rain will occur at Washington, D. C., during the hours 0700 through 1900 EST "tomorrow."

At the time of issuing the forecast for which this study is designed as an aid, the forecaster has available to him the surface or sea level weather map for 0130 EST and the analyzed upper air charts for 2200 EST of the pre-

ceding evening. This investigation is limited to the systematic utilization of data from the 2200 EST upper air charts and reference to surface weather conditions has been omitted except wherein it may aid in clarification of the text. The forecaster is left to his own devices in applying the surface data or in otherwise modifying the objective forecast of "rain" or "no rain."

Surface data are not used for several reasons. First, it was decided to determine the extent to which upper air information alone could be used in making a forecast for the selected 12-hour period. Second, if a forecast method is to be of maximum practical use it should be a method that can be used before the last few minutes of the forecaster's allotted time. Since the upper air information is all available before the surface map, the forecast based on the upper air information can be completed before the surface map is analyzed. Thus the system is in part designed to fit the operational program of a forecast center which issues forecasts for a broad area, the deadline for which is not long after the completion of the surface weather map. During this brief period, time is not available for the application of objective systems for more than a small portion of the area for which forecasts must be issued. It is possible that the addition of surface parameters could improve the system described in this study, but in a limited attempt to do this, no additional advantages were gained. In many of the cases studied precipitation or surface disturbances developed after the forecast deadline so that extrapolation of surface information was not helpful.

The results might actually suggest that for forecasts as far in advance as those discussed here, the surface data can contribute little information in addition to that supplied by the upper air.

The basic and test data used in this study include all Octobers 1945 through 1949. Data were not readily available for years prior to 1945 and since this study was started after September 1, 1950, and the objective was to develop a system that could be used beginning October 1, 1950, a limited amount of time was available. Years 1945, 1947, and 1949 were used as dependent data and years 1946 and 1948 as test data. The study in which 155 individual cases were examined was completed and made available for use by the regular forecasters at Washington National Airport prior to October 1, 1950. The results when applied to October 1950 were very encouraging and the hope is that the system can be made even better with further investigation.

DEVELOPMENT OF FORECASTING SYSTEM

METHOD OF APPROACH

In selecting variables which might be related to the actual occurrence of precipitation during the 12-hour period beginning 33 hours after the most recent (2200 EST) upper air soundings, it was soon discovered to be extremely difficult, by the specified forecast deadline time, to delineate the necessary conditions for measurable rain to fall during the period in question. Of course, timing or movement of systems was extremely important, i. e., if conditions moved too fast rain would end before beginning of the period, or, if too slow then rain would not begin until after the end of the 12-hour period. After many attempts to base the forecast of rain on a number of "causal factors" it was decided that this method was not appropriate during the month of October but that much better results might be obtained by determining what factors would *prevent* occurrence of rainfall during the period. Thus, lacking a "preventative" factor, rainfall was likely during the period in question. Although some meteorologists are perhaps not accustomed to thinking of forecasting in the sense of determining that certain conditions such as rainfall will *not* occur, it is usually a part of the forecaster's "thought process" whether he realizes it or not. For example, a forecaster in checking the latest synoptic charts, determining movement, deepening, filling, etc., and deciding whether a given system will produce rain, must also go through the process of determining whether or not this particular rain development will have passed through or be short of, north of, south of, etc., the forecast area during the period in question.

STRATIFICATION OF WEATHER SITUATION

As stated previously, the method being described involves the use of upper air data read from constant pressure charts at 850 mb. and higher. At the outset many of the situations were eliminated as "no rain" cases by the simple device of indexing the flow pattern west of Washington at 850 mb. This was done by noting the height of this surface at Nashville, Tenn., and Sault Ste. Marie, Mich., both as compared with the height at Washington, D. C., at the corresponding time, 2200 EST. (See fig. 1.) Thus if heights at both Nashville and Sault Ste. Marie are higher than at Washington a broad northwesterly flow usually is present west of Washington, which normally prevents the occurrence of a precipitation-producing situation in the Washington area during the period 33–45 hours hence. A second type, wherein the height at Nashville is less than Washington and that at Sault Ste. Marie is greater than Washington, often precedes the occurrence of rain at Washington and therefore further factors must be checked in order to determine whether a rain-producing system will be influencing the Washington area during our 12-hour forecast period. The third type, which meets neither of the above conditions, and therefore includes all cases not classified as one of the first two categories requires a more detailed check. (See fig. 1.)

Table 1 outlines roughly the problem which remains after this stratification, and in the sections which follow methods for forecasting are described in greater detail under the corresponding type.

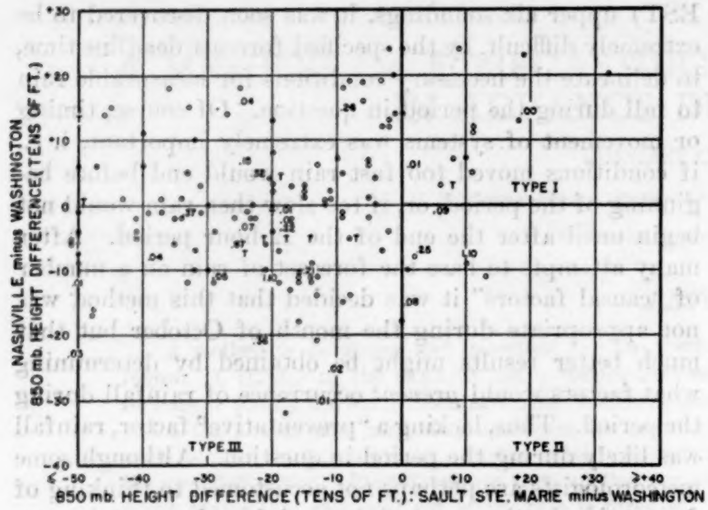


FIGURE 1.—Scatter diagram showing distribution of cases considered in the study as a function of two 850-mb. height differences, and stratification into three basic types. For the plotted cases, open circle indicates no rain during forecast period, "T" indicates trace of rain, and number indicates measurable amount of rain (inches).

Table 1.—Stratification of October cases 1945–49 into three basic types

Type	Number of cases	Number of "rain" cases	Frequency of rain (%)
I	13	2	15
II	8	4	50
III	134	19	14
All types	155	25	16

TYPE I PROCEDURE

Type I includes all instances wherein the 850-mb. height at Nashville and the 850-mb. height at Sault Ste. Marie are both greater than that at Washington. With this type, a forecast of "no rain" is usually sufficient (and in an objective application of the system, always indicated) since northerly or northwesterly flow is usually present aloft in such a way as to prevent a trough from being sufficiently close 33–45 hours in the future to bring in the necessary moisture, vertical motion, etc., to produce precipitation.

TYPE II PROCEDURE

In type II cases the 850 mb. height at Nashville is lower than at Washington and that at Sault Ste. Marie is greater than at Washington.

This type usually occurs along with a low pressure system which is threatening to move into the Washington area from the south, and is an ideal type for the production of heavy amounts of rain at Washington. Rain usually occurs at Washington subsequent to map time (0130 EST), though it may either move too fast to still be occurring during the forecast period, or the entire rain producing system may be displaced south of our area. These two possibilities are covered by the following rules:

1. If the 850-mb. heights at Omaha, Sault Ste. Marie, and Washington show 24-hour rises, forecast "no rain" as any rain producing system will be pushed south of our area.
2. If Washington shows a greater 24-hour height fall than Nashville at 850 mb. and there are no falls west and northwest of Nashville (at Omaha, Little Rock, Chicago, and Columbia) greater than the Nashville fall, forecast "no rain" since the entire rain-producing system, if any, will move through before the beginning of the forecast period.

TYPE III PROCEDURE

Of the 155 cases examined in this study, 134 or 87 percent were type III. Type III consists of all cases not previously classified as type I or II and by definition includes all cases wherein the 850-mb. height at Sault Ste. Marie is equal to or less than that at Washington.

Forecasting whether rain will occur with this type of situation is again essentially an elimination process. Thus most of the steps in the forecasting procedure outlined here involve the question of whether rain can be eliminated. It follows therefore that if one reaches the end of the list of proposed questions without eliminating rain, the forecast should be for rain to occur within the specified 12-hour period "tomorrow."

1. Follow the 700-mb. contour through Washington upwind. If this contour is through or north of Chicago *and* Omaha forecast "no rain." Otherwise check step 2.
2. If the 850-mb. surface at Nashville is 30 feet or more higher than that at Miami, forecast "no rain." Otherwise check step 3.
3. Next follow the 850-mb. contour through Nashville upwind. If this contour is through or north of Oklahoma city, follow steps shown below under *North Type*.[1] Otherwise follow the steps shown under the heading *South Type*.

North Type (Nashville 850-mb. contour upwind is through or north of Oklahoma City.)[1]

(a) If there is a trough at 500 mb. between the Rocky Mountains and Chicago, check step (b). Otherwise forecast "no rain."

(b) If the trough at 500 mb. exists, check the 500-mb. contour through Greensboro, N. C., upwind. If it extends southward to below the 30th parallel (30° N. latitude),[2] check step (b.1). Otherwise check step (b.2).

(b.1) (500-mb. contour through Greensboro upwind goes south of 30° N.) If the 24-hour height tendency at 700 mb. over Oklahoma City

[1] On occasion the Nashville contour extends directly northward or northeastward rather than northwestward as might be pictured here. Such cases are also classified as being the *North Type*.

[2] Little difficulty should be encountered here, even though a strict definition of the longitudinal limits is not given. Roughly it is that portion of the 30th parallel between 75° and 115° W. longitude which is being considered.

is negative *or* if the 24-hour height tendency at 850 mb. at Little Rock is negative, forecast "rain." Otherwise forecast "no rain."

(b. 2) (500-mb. contour through Greensboro upwind stays north of 30° N.) Check the 24-hour height tendencies at North Platte, Dodge City, and Oklahoma City at 850 mb., 700 mb., and 500 mb. If two of three stations show minus tendencies at all three levels forecast "rain." Otherwise forecast "no rain."

South Type. (Nashville 850-mb. contour upwind is not north of or through Oklahoma City.)

(a) Check 850-mb. 24-hour height changes at Nashville and Chicago. If Chicago height is falling and that at Nashville rising, forecast "no rain."

(b) Check 24-hour height changes at 850 mb. at Minneapolis, Omaha, Dodge City, Little Rock, and Nashville. If they are all rises, forecast "no rain," *except* if the 850-mb. and 700-mb. contours through Toledo upwind enter the Gulf of Mexico, check step (c).

(c) If step number 2 (above) showed 850-mb. surface at Nashville to be 10 or 20 feet higher than at Miami and if Chicago 850-mb. height is greater than Miami, forecast "no rain."

(d) If the 850-mb. contour through Washington upwind is through or north of Albany or north of Buffalo and International Falls, forecast "no rain."

(e) If the height of the 850-mb. surface at Atlanta is 30 feet or more higher than that at Nashville and Miami, and the 700-mb. contour through Nashville upwind is through or north of Fort Worth, forecast "no rain."

If (a), (b), (c), (d), or (e) does not eliminate rain, then the forecast must be "rain."

For the reader who is concerned by the elaborate treatment given to type III cases as compared with the automatic "no rain" forecast for type I cases, one need perhaps mention only the far greater number of type III cases available for study. Furthermore in the two rain cases subsequent to type I maps, amounts of rain measured at Washington were very light, 0.01 and 0.05 inch for the 12-hour period.

METEOROLOGICAL REASONING IN TYPE III RULES

Because the forecasting system for use in type III cases is elaborate, a discussion of the meteorological reasoning involved in its development may help other forecasters to relate the rules to their own forecasting experience. The numbering of the following paragraphs corresponds to the type III rules listed in the preceding section.

1. If Washington upwind flow at 700 mb. is through or north of Chicago and Omaha there is usually insufficient time for an air channel from the Gulf to "open" and permit moisture to arrive in the Washington area along with other conditions conducive to formation of precipitation within 45 hours.
2. When Nashville 850-mb. height is 30 feet or more greater than Miami the flow aloft ordinarily holds waves, overrunning, etc., to the east and south of Washington during the verification period and there is usually insufficient time for rain to develop and move in from the west or southwest.
3. North Type Cases:

When the Nashville 850-mb. upwind flow is through or north of Oklahoma City any rain producing troughs in the eastern half of the country usually move too far east to cause precipitation in the Washington area during the verification period. However, when troughs "hang back" considerably at upper levels, and pressure falls (height falls) are introduced into these troughs, waves or new fronts develop under certain conditions and clearing does not take place as soon as when these conditions do not exist. The rules listed under the *north type* cases are for the purpose of detecting the cases which will produce rain when a trough at 500 mb. is lagging as far back as the Chicago–Denver area.

South Type Cases:

(a) This rule was developed to take care of disturbances moving in a northeastward direction in such fashion that rain will usually be confined to areas north of Washington and Baltimore or if rain occurs it will usually have ended before forecast period.

(b) This rule serves generally to take care of filling and/or sufficient eastward movement of a trough so as to rule out rain.

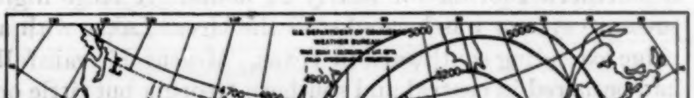


FIGURE 2.—850-mb. chart for 2200 EST, October 3, 1948. Contours are drawn for 100-ft. intervals and labeled in feet. Three-digit numbers plotted at selected stations give observed height in tens of feet, and the numbers preceded by + or − indicate the 24-hour height change at the stations.

(c) This is similar to rule 2 above and since 10 or 20 feet is more or less in the transitional zone between 0 and 30, it was considered advisable to include an additional variable, making two conditions necessary to eliminate precipitation.

(d) Again in this case there is usually a strong northerly flow caused by a Low just moving off the coast at map time and there is insufficient time for another disturbance to move into the area by the beginning of the forecast period.

(e) This implies a blocking High in the East and relatively dry flow into Nashville at 700 mb.

EXAMPLES OF APPLICATION

The examples of application of the forecasting system to actual situations which are given in this section may help clarify any questions the reader may have about the procedures for types II and III.

EXAMPLE OF TYPE II CASE

The 850-mb. chart for 2200 EST, October 3, 1948 (fig. 2) shows Nashville height at 5,100 feet, Washington 5,180 feet, and Sault Ste. Marie 5,280 feet. Since Nashville is lower than Washington and Sault Ste. Marie higher than Washington this falls into the type II category, which is the rain type. The steps in forecasting are as follows:

1. Omaha 24-hour height change is negative, therefore rain is not eliminated.
2. Washington 24-hour height change is "plus" and Nashville "minus," therefore this does not eliminate rain.

Since these two steps do not eliminate rain the system automatically gives a "rain" forecast.

A study of the surface map for 0130 EST, October 4 (fig. 3) reveals that at the time the forecast was made there was a nearly stationary front extending from northern Florida eastward to near Bermuda; this front had been in northern Florida for nearly 24 hours. A large high pressure system was located over the Great Lakes with a ridge extending southward to Texas. Measurable rainfall had occurred in central and southern Georgia but little or no rain from northern Georgia northward.

By 0130 EST, October 5 (fig. 4) a well developed wave had formed and was located just south of Hatteras and rain was just beginning in Washington. By 1930 EST, October 5, the rain had spread northward through all of Pennsylvania and the total fall at Washington during the 12-hour verification period was 1.10 inches. Rainfall at both Richmond and Baltimore was 1.15 inches.

EXAMPLES OF TYPE III CASES

The case shown on the constant pressure charts for 2200 EST, October 26, 1949, from which a forecast for the "day" period of October 28 was made, provides considerable interest. Heights on the 850-mb. chart in figure 5

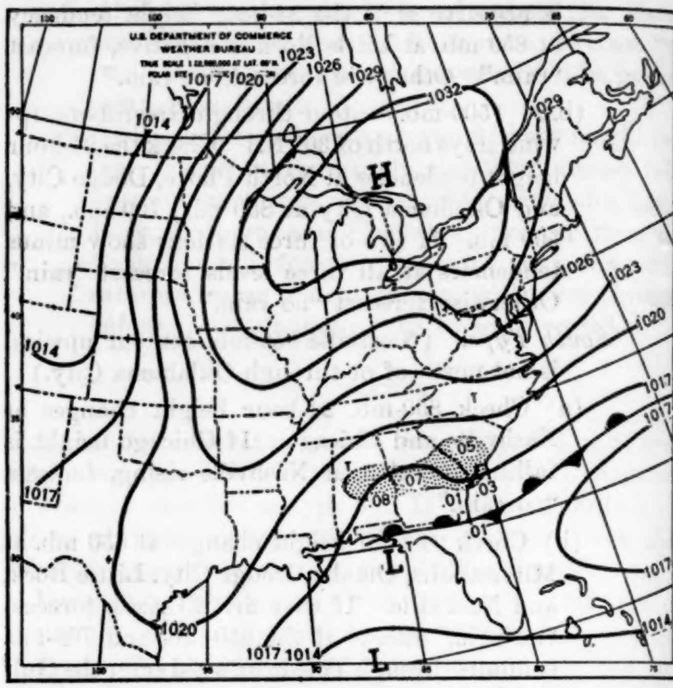


Figure 3.—Surface chart for 0130 EST, October 4, 1948. Isobars are labeled in millibars. The stippling indicates area of active precipitation, and plotted numbers show 6-hour amounts at selected stations.

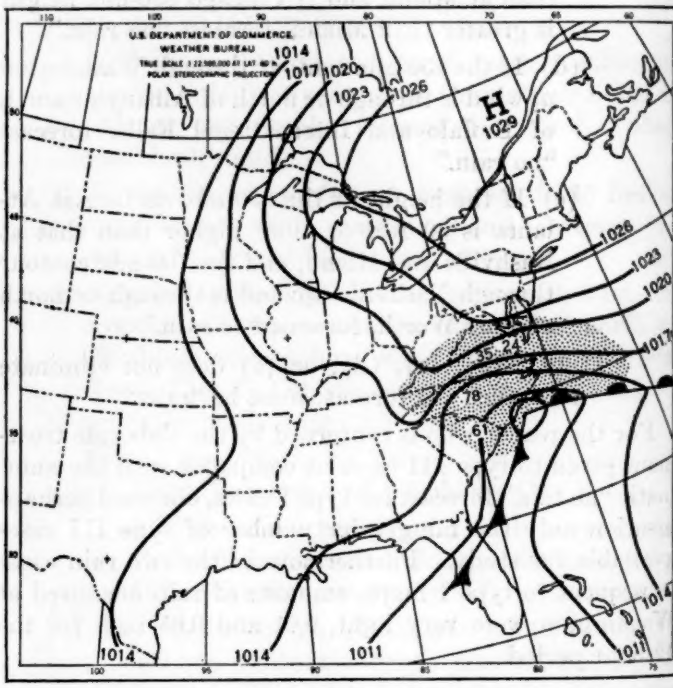


Figure 4.—Surface chart for 0130 EST, October 5, 1948.

show that the height at Sault Ste. Marie is less than that at Washington. (Washington 5,100 ft. and Sault Ste. Marie 4,880 ft.) This classifies the situation as type III.

The surface map available at forecast time is the 0130 EST map of October 27 (fig. 6). The surface map is not used in this system but it will be interesting to note that

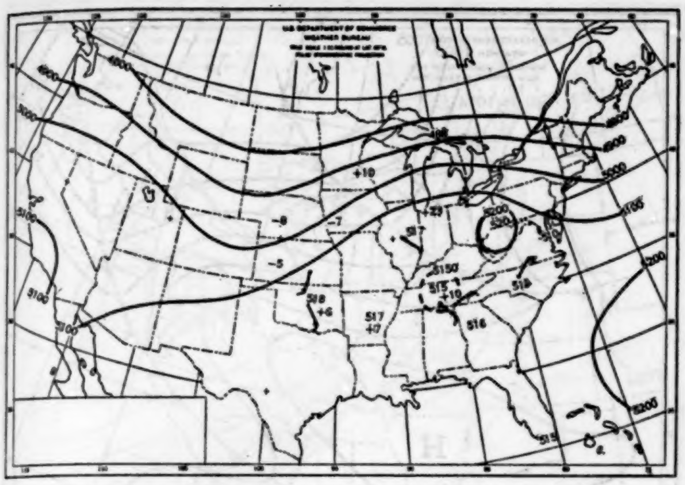


FIGURE 5.—850-mb. chart for 2200 EST, October 26, 1949.

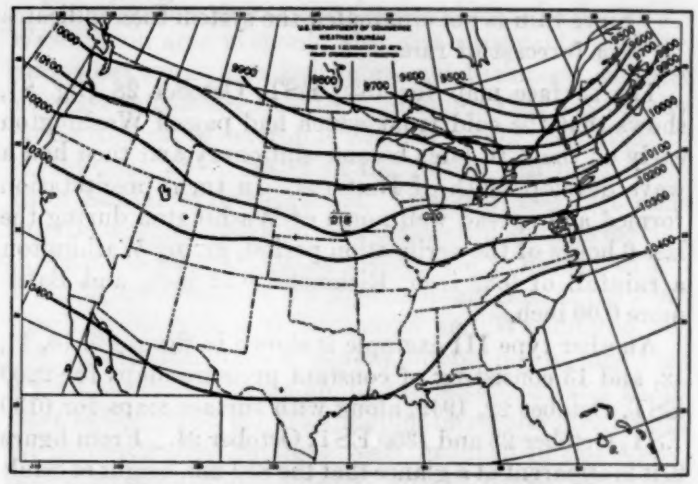


FIGURE 7.—700-mb. chart for 2200 EST, October 26, 1949. Contours are labeled in feet. Plotted numbers selected stations give observed height in tens of feet (with the 10-thousand digit omitted).

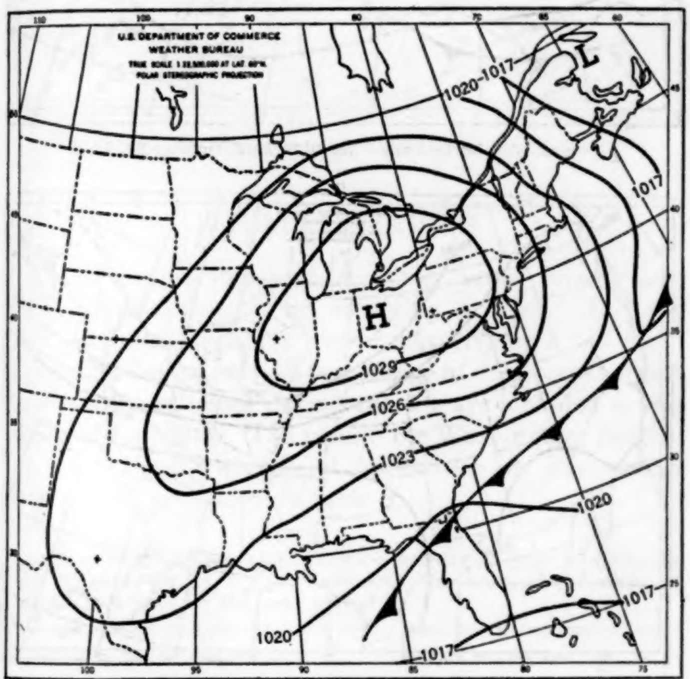


FIGURE 6.—Surface chart for 0130 EST, October 27, 1949.

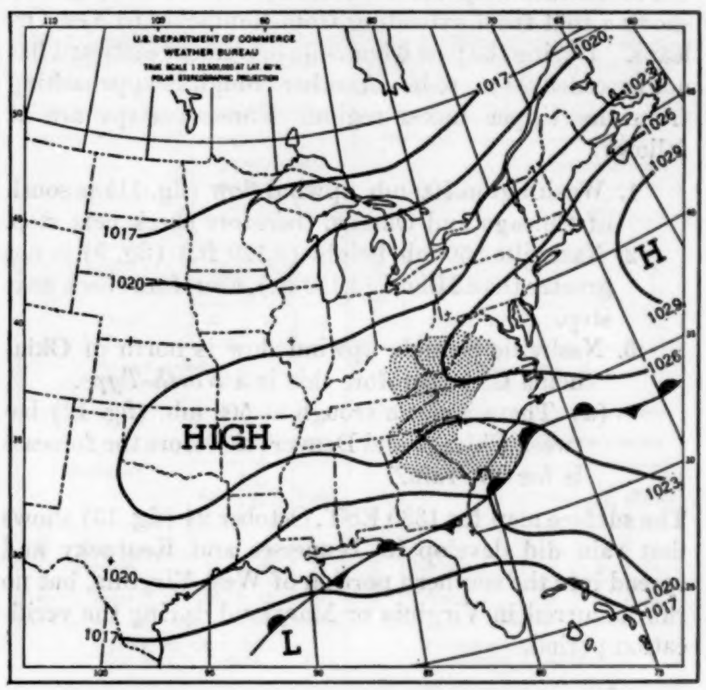


FIGURE 8.—Surface chart for 1330 EST, October 28, 1949.

a large high pressure system covers the eastern half of the country and a cold front is well east of Washington and extending southwestward to near Jacksonville. The air is quite dry over the east and pressures are rising and the cold front has had an eastward movement of 30 to 40 m. p. h. during the past 12 hours. In this case it appears perfectly logical to forecast "no rain" for tomorrow. The 700-mb. chart for 2200 EST of the 26th is shown in figure 7.

The check of steps in forecasting for type III cases as applied here follows:

1. Washington 700-mb. upwind flow is south of Chicago and Omaha, therefore check step 2.
2. Nashville 850-mb. height (5,150 ft.) is not 30 feet or more higher than Miami (5,150 ft.); therefore we must proceed further.
3. Nashville 850-mb. upwind flow is not through or north of Oklahoma City, therefore this is classified as a *South Type*.
   (a) Chicago 24-hour height change is plus, so this does not eliminate rain.
   (b) Dodge City and Omaha 850-mb. heights are falling, so this does not eliminate rain.
   (c) Does not apply and does not eliminate rain.
   (d) Washington 850-mb. upwind flow is south of Albany, Buffalo, and International Falls, so this does not eliminate rain.
   (e) Atlanta 850-mb. height (5,160 ft.) is only 10 feet higher than Nashville (5,150 ft.) and Miami (5,150 ft.), so this does not eliminate rain.

Since rain is not eliminated the system then indicates a forecast of rain.

The surface map for 1330 EST, October 28 (fig. 8), shows that the cold front which had passed Washington early on the 27th later became stationary and then had a wave develop south of Hatteras. In turn, precipitation formed and spread well north of Washington during the last 6 hours of the verification period, giving Washington a rainfall of 0.32 inch, Richmond 0.12 inch, and Baltimore 0.09 inch.

Another type III example is shown in figures 9, 10, 11, 12, and 13 consisting of constant pressure maps for 2200 EST, October 22, 1949, along with surface maps for 0130 EST, October 23 and 1330 EST, October 24. From figure 9, it is apparent at a glance that the 850-mb. height at Sault Ste. Marie (4,520 ft.) is less than that at Washington (4,970 ft.) and therefore this is classified as type III.

The surface map for 0130 EST, October 23 (fig. 10) shows a cold front extending from Nantucket to New Orleans. During the past 6 hours its movement eastward has not exceeded 20 m. p. h. Another trough is approaching from the Upper Lakes region. Forecast steps are as follows:

1. Washington 700-mb. upwind flow (fig. 11) is south of Chicago and Omaha, therefore check next step.
2. Nashville 850-mb. height (5,120 ft.) (fig. 9) is not greater than Miami (5,150 ft.), therefore check next step.
3. Nashville 850-mb. upwind flow is north of Oklahoma City therefore this is a *North Type*.
   (a) There is not a trough at 500 mb. (fig. 12) between Chicago and Denver; therefore the forecast is for "no rain."

The surface map for 1330 EST, October 24 (fig. 13) shows that rain did develop in Tennessee and Kentucky and spread into the southern portion of West Virginia, but no rain occurred in Virginia or Maryland during the verification period.

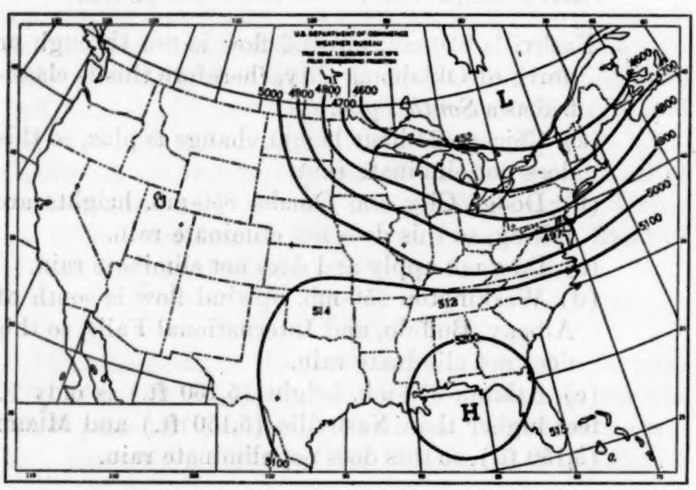


FIGURE 9.—850-mb. chart for 2200 EST, October 22, 1949.

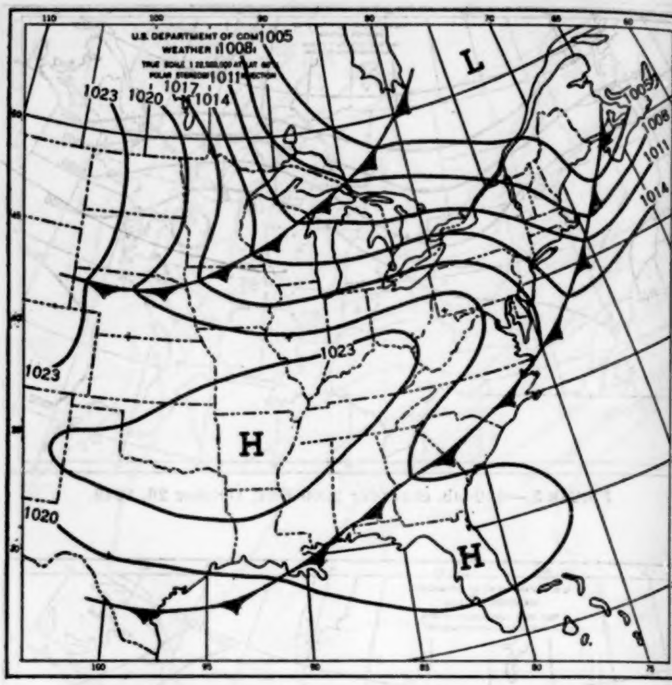


FIGURE 10.—Surface chart for 0130 EST, October 23, 1949.

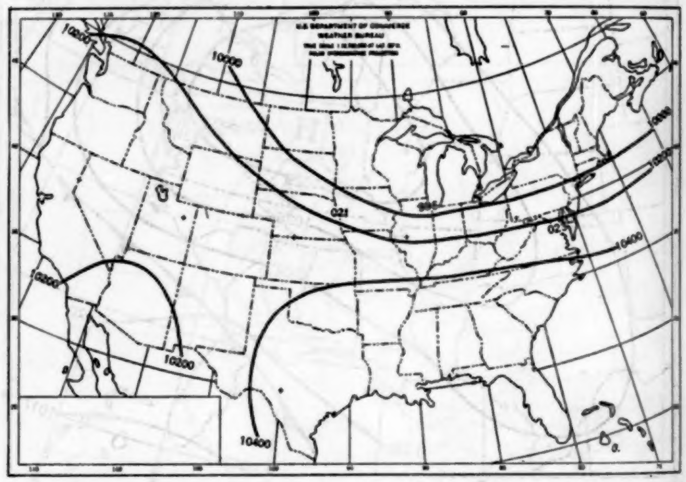


FIGURE 11.—700-mb. chart for 2200 EST, October 22, 1949.

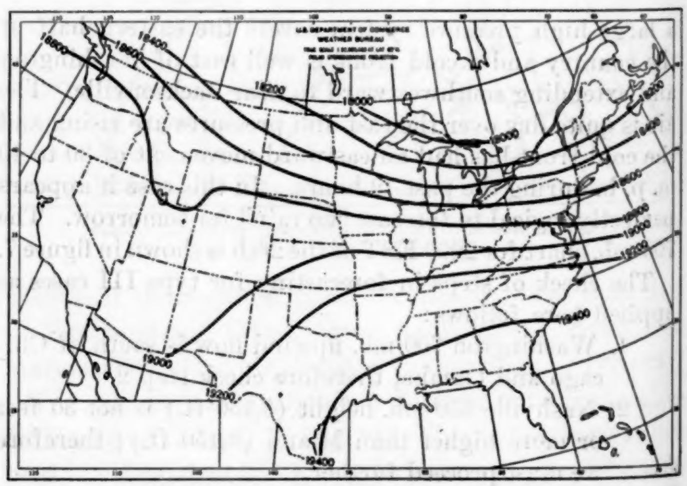


FIGURE 12.—500-mb. chart for 2200 EST, October 22, 1949. Contours are labeled in feet.

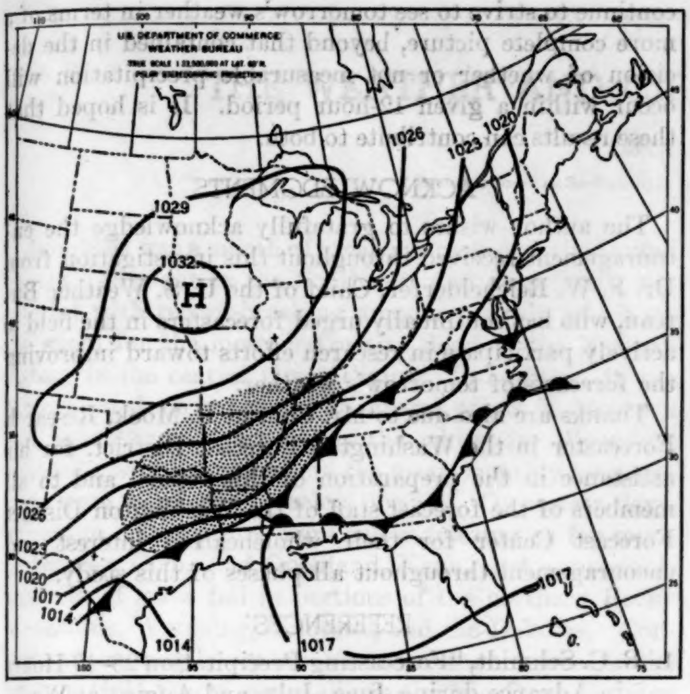


FIGURE 13.—Surface chart for 1330 EST, October 24, 1949.

RESULTS OF TESTING

A rigid verification, considering measurable rain (≥ 0.01 inch) at Washington as verifying a "rain" forecast and no precipitation or a "trace" as verifying a "no rain" forecast, shows an over-all percentage of 88 percent correct forecasts for all cases during the 5 years included in the basic and test data. The results for Washington, including comparison with official forecasts made during the same period, are shown in table 2.

TABLE 2.—*Contingency tables showing results of system forecasts for Washington, D. C., for basic and test data, and results of official forecasts for the same period*

Basic data, October 1945, 1947, 1949	Official forecast: Rain	No rain	Total	Test data, October 1946, 1948	Official forecast: Rain	No rain	Total
Observed: Rain	3	12	15	Observed: Rain	7	3	10
Observed: No rain	11	67	78	Observed: No rain	4	48	52
Total	14	79	93	Total	11	51	62
Percent correct = 75; Skill score = 0.08				Percent correct = 90; Skill score = 0.61			

	System forecast: Rain	No rain	Rain		System forecast: Rain	No rain	Total
Observed: Rain	12	3	15	Observed: Rain	9	1	10
Observed: No rain	9	60	78	Observed: No rain	5	47	52
Total	21	72	93	Total	14	48	62
Percent correct = 87; Skill score = 0.60				Percent correct = 90; Skill score = 0.70			

Although this system was developed specifically for the Washington area it should also give reasonably good results when applied to Baltimore and Richmond, as these cities are sufficiently close to Washington that it is usually rather difficult to determine whether a rain area affecting Washington 33–45 hours in the future will or will not affect Baltimore or Richmond. However, there are some situations which result in rain-producing systems moving to the north of Washington giving rain at Baltimore and Washington, and there are others moving close to the south which produce rain at Richmond and Washington but just miss Baltimore. It is very interesting to note that when the same rules are applied to Richmond and Baltimore as developed for Washington the results give identical percent scores for the 5 years included in this study, that is 85 percent as compared with 88 percent at Washington. The results for Baltimore and Richmond are summarized in table 3.

TABLE 3.—*Contingency tables showing results of system forecasts for Richmond, Va., and Baltimore, Md., for basic and test data*

Basic Data, October 1945, 1947, 1949 — Richmond	System forecast: Rain	No rain	Total	Test Data, October 1946, 1948 — Richmond	System forecast: Rain	No rain	Total
Observed: Rain	12	5	17	Observed: Rain	8	3	11
Observed: No rain	9	67	76	Observed: No rain	6	45	51
Total	21	72	93	Total	14	48	62
Percent correct = 85; Skill score = 0.53				Percent correct = 85; Skill score = 0.55			

Baltimore	System forecast: Rain	No rain	Total	Baltimore	System forecast: Rain	No rain	Total
Observed: Rain	10	4	14	Observed: Rain	9	3	12
Observed: No rain	11	68	79	Observed: No rain	5	45	50
Total	21	72	93	Total	14	48	62
Percent correct = 84; Skill score = 0.48				Percent correct = 87; Skill score = 0.62			

RESULTS OF APPLICATION IN OCTOBER 1950

As was stated earlier the method described in this report was completed and tested prior to October 1, 1950, in order that it might be available for use in actual forecasting at that time. It is therefore of considerable interest to examine the results obtained during that month, which in addition to being a month which could logically be reported as test data, is a month wherein the computations were actually routinely performed by the forecasters responsible for the issuance of the official forecasts for the period under consideration. The contingency table shown in table 4 indicates the results thus obtained.

Identical contingency tables were obtained when the results of applying the system to Baltimore and Richmond

TABLE 4.—*Contingency table showing results of system forecasts for Washington, D. C., from routine application during October 1950*

		System forecast		
		Rain	No rain	Total
Observed	Rain	3	2	5
	No rain	1	25	26
	Total	4	27	31

Percent correct = 90
Skill score = 0.62

were analyzed, even though there was a slight difference in the actual dates on which precipitation was reported at Richmond as compared with Baltimore and Washington. It is readily seen that the objective forecasts for Washington were 90 percent correct when applied not only to Washington but also to Richmond and Baltimore.

CONCLUSIONS

The results of this and other studies of this kind which have been referred to in the introduction to this report suggest the possibility that very significant improvement in the accuracy of forecasts of tomorrow's weather can be achieved through a systematic utilization of upper air data within the framework of our present knowledge of basic meteorological processes. Even though there has been but casual reference to the surface weather chart in this report, the author believes that the forecaster should continue to strive to see tomorrow's weather in terms of a more complete picture, beyond that contained in the decision of whether or not measurable precipitation will occur within a given 12-hour period. It is hoped that these results can contribute to both.

ACKNOWLEDGMENTS

The author wishes to gratefully acknowledge the encouragement received throughout this investigation from Dr. F. W. Reichelderfer, Chief of the U. S. Weather Bureau, who has continually urged forecasters in the field to actively participate in research efforts toward improving the forecasts of tomorrow's weather.

Thanks are also due to Mr. Conrad P. Mook, Research Forecaster in the Washington Forecast District, for his assistance in the preparation of this report, and to all members of the forecast staff of the Washington District Forecast Center for their wholehearted interest and encouragement throughout all phases of this study.

REFERENCES

1. R. C. Schmidt, "Forecasting Precipitation 28–40 Hours in Advance during June, July, and August at Washington, D. C.," Weather Bureau Airport Station, Washington, D. C., 1950. (Unpublished manuscript.)
2. R. C. Schmidt, "A Method of Forecasting Occurrence of Winter Precipitation Two Days in Advance," *Monthly Weather Review*, vol. 79, No. 5, May 1951, pp. 81–95.

THE WEATHER AND CIRCULATION OF JUNE 1951

LeROY H. CLEM

Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.

June 1951 was a month of great contrasts over the United States. Drought in the Southwest and deep South was coupled with record-breaking amounts of rain which set the stage for the most destructive flood in the Nation's history in the central Great Plains. In addition, it was the coldest June on record at several points in Montana and Nebraska and very nearly the coldest for Wyoming, Colorado, and Kansas where the mean monthly temperatures were more than 5° below normal. On certain days, minimum temperatures were below freezing as far south as Denver, Colo., and Goodland, Kans., and appreciable amounts of snow fell in portions of the northern Rocky Mountains, Wyoming, Colorado, and the Dakotas. Conversely, the month was much warmer than normal in the western Gulf States, especially in the Big Bend Country of Texas, where Presidio's 116° F. on the 20th nearly broke the June record. Stations in southeastern New Mexico recorded daily maximum temperatures which equalled the all time high for the month. The normal June temperatures at Dodge City and Presidio are 73° F. and 84° F. respectively, and differ by 11°. This month the difference was 22° F., as Dodge City recorded a 6° below-normal reading of 67° F. while Presidio observed a warm 89° F.

These anomalous temperature fields and the attendant weather were closely associated with some of the more prominent features of the mean circulation over North America and adjacent oceans during June (fig. 1). The most pronounced and probably most significant feature was the unusually strong ridge in the eastern Pacific at all levels of the atmosphere up to at least 40,000 feet. (Charts XI–XV.)[1] Figure 1 shows that the heights in this ridge at 700 mb. were as much as 300 feet above normal, while Chart XI inset indicates that at sea level the pressures departed from the normal in a similar fashion by as much as 9 mb.

Immediately upstream from this ridge a deep trough extended from the Aleutian Low, which was south of its normal position, to the Hawaiian Islands. As might be expected from the large amplitude of this Pacific trough-ridge system, a well defined trough was located downstream, extending from south central Canada through the southwestern United States. Since heights were below normal in this trough as well as throughout northwestern Canada, strong northwesterly and northerly flow relative to normal was observed from the Gulf of Alaska and northwest Canada to Montana, Wyoming, and Colorado. This anomalous flow brought surge after surge of abnormally cold air into the northern Rocky Mountain and Great Plains States [1]. The cold air masses worked their way southward through the trough and then, under the influence of the prevailing circulation, they moved eastward across the central Great Plains. The southern boundary of their invasions was generally in Oklahoma. The flow between the above-normal heights centered in the Gulf of Mexico and the below-normal heights in the trough in the Southwest was more southerly and southwesterly than normal over Texas and Oklahoma. This circulation helped divert the cold air masses toward the east and brought the hot moisture-laden air from the Gulf of Mexico into contact with the cold surges from the north. The recurring interaction of these contrasting streams of air resulted in devastatingly heavy rains in the central Great Plains which, after an especially wet May [2], led to extensive flooding in Kansas, Missouri, and Nebraska.

Rainfall was generally greater than normal throughout most of the region from the Gulf Coast of Texas northward to Montana and Minnesota, excepting North Dakota (Charts III A and B). In the northern part of this above-normal precipitation area, the rain was associated with the mean trough and negative height anomalies. In the south shower activity, occurring in the warm unstable Gulf air, was responsible for much of the rain. The rainfall was especially heavy near the central Texas Gulf coast where, early in the month, a cold front set off such record-breaking downpours as 6.18 inches at San Antonio in 24 hours.

It was in the central part of this region that the main interplay of the two contrasting air masses occurred. This central area, including nearly the entire State of Kansas, received over 200 percent of its normal rainfall amount. Storms ravaged practically all parts of Kansas throughout the month. Records from all sections of the State showed that the average rainfall for Kansas during June was 9.69 inches, nearly 6 inches above the normal and the greatest amount for any one month in the 65 years that records have been maintained. This amount was nearly an inch more than that for the next wettest month, July 1950, and nearly 2 inches more than for the previous wettest June which was in 1908. The appropriately named community of Climax, just east of Wichita, reported 16.5 inches for the greatest monthly total of all, while more than one-

[1] See charts I–XV following p. 132 for analyzed Climatological Data for the month.

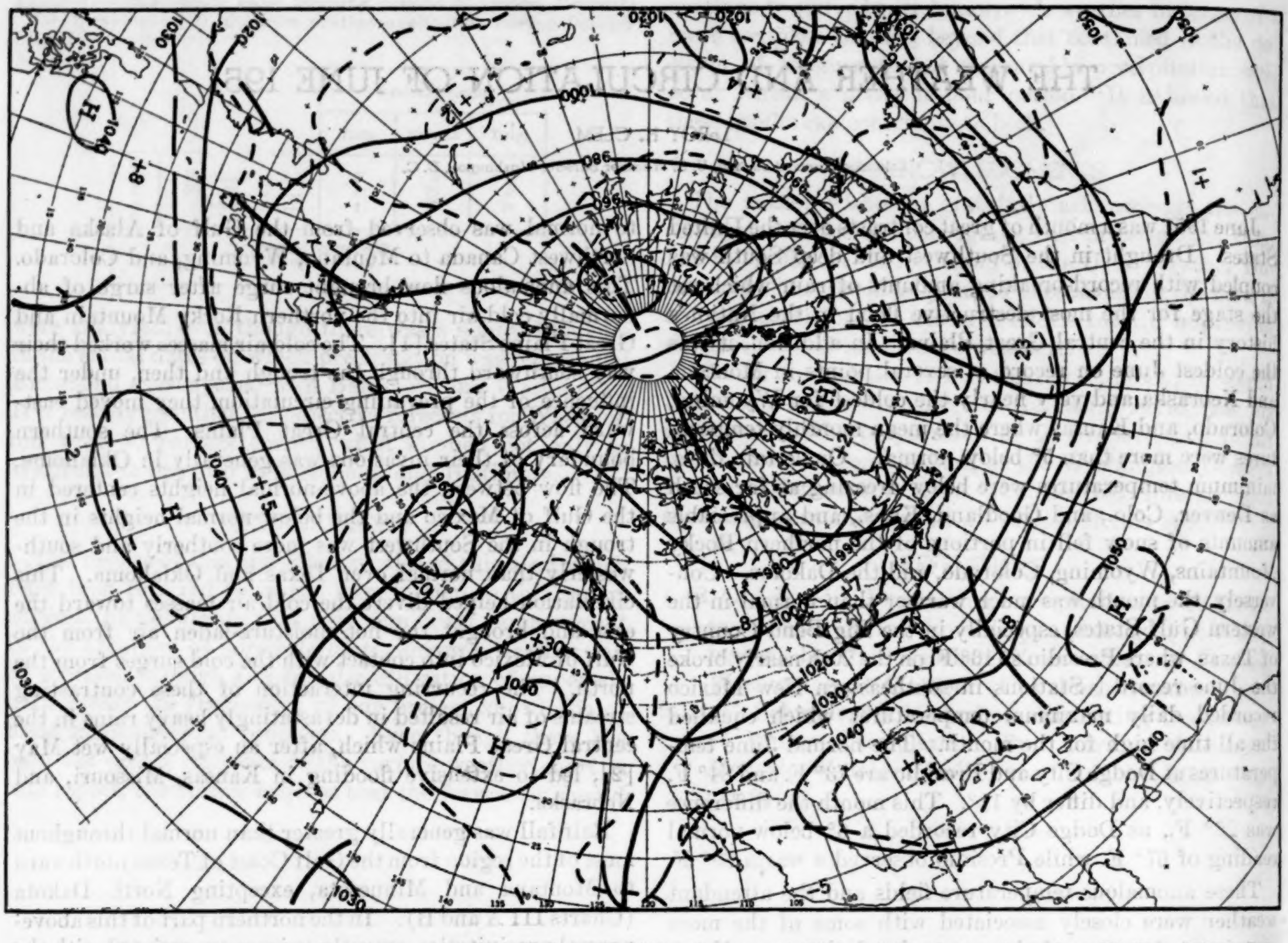


FIGURE 1.—Mean 700-mb. chart for the 30-day period May 28–June 27, 1951. Contours at 200-foot intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departures from normal at 100-foot intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

third of the stations reported monthly totals in excess of 10 inches. The nearly-routine weather summary was "severe thunderstorms, frequently accompanied by hail, high winds, and sometimes tornadoes". In addition to excessive rainfall and flood losses, conservative damage estimates from 42 tornadoes, 34 hailstorms, 20 severe windstorms and 34 lightning strikes totalled $26,439,275. One hundred and seventeen injuries were reported, many from such observed conditions as 90 m. p. h. winds driving the hail which occasionally was reported to be golf ball size or larger. Lightning caused two deaths and tornadoes were responsible for six more. Such were the disastrous results when the general circulation oriented itself in such a manner as to bring together two completely opposite streams of air; one, the abnormally cold air from the Gulf of Alaska and northwest Canada which tenaciously clung to the ground like a heavy liquid, and the other, the warm moist stream of air from the Gulf of Mexico which, being lighter, was forced up over the tapered edge of the cold air as the two streams met. Finally, as this warm air cooled beyond the condensation point, rain and energy were released, sometimes with unusual violence.

In contrast to the very wet conditions in the central Great Plains, extreme drought prevailed over nearly all of the Southwest. At Albuquerque, located in the region of prolonged drought, the rainfall during the first 6 months of 1951 was less than 40 percent of the normal. It was so dry toward the latter part of the month that Albuquerque several times reported relative humidities under 10 percent. The record low of 3 percent was observed during the night of June 22. In parts of Arizona and New Mexico more cloud cover than normal (Chart VI–B) was observed. This cloudiness was associated with rather weak activity moving in the general flow east of the mean trough in the Southwest and resulted in temperature departures from normal of −1°. Unfortunately this cloud cover was not effective in bringing the much-needed rainfall to the drought area. In general, scarcely more than a trace of rain was reported for most of the region during the entire month of June. It is interesting to

note that the region of drought in the Southwest was under the influence of anticyclonic relative vorticity at 700 mb. (fig. 2). In addition, the trajectory of the air both at sea level and aloft was from a dry source rather than from the Gulf of Mexico.

Another region where the air was warmer and drier than normal was the Far West. The mountains acted as a barrier in keeping the cold air restricted on their eastern side. In the northern portion, warm weather was associated with above-normal heights on the east side of the Pacific ridge. The attendant subsidence resulted in clear skies and increased sunshine (Charts VI and VII). Also the flow relative to normal brought into the area air from over warmed land surfaces rather than directly from over the cold waters off the west coast. During the middle of the month, under the clear skies associated with a warm High over the interior Plateau region, the temperature departure was nearly 10° above normal. The warmer-than-normal air in the southern part of the Far West (Chart I-B) was associated with the well developed thermal trough (Chart XI). The existence of the sea breeze can be seen from the wind roses (Chart XI) along the California coast. The effect of this sea breeze on the temperature anomaly (Chart I inset) and on the percentage of clear skies (Chart VI) is very pronounced along the west coast. These features are characteristic of this type of synoptic situation, especially when the water temperatures are much colder than the land during the day. Most of the rainfall in the central California-Nevada area came early in the month with a storm passage (Chart X), while the rainfall in the interior of Washington came from occasional storms moving down the east side of the Pacific High. In contrast, drought conditions and forest fire hazard prevailed in northern California and western Oregon in connection with above-normal heights and anticyclonic relative vorticity at 700 mb. (fig. 2). Another good indication of the nature of the air in these regions is the anomalous offshore dry flow at sea level (Chart XI inset).

Following the sea level pressure anomaly chart to the eastern half of the Nation, we find a band of minimum values from the flood areas of the Great Plains through the middle Atlantic seaboard and out into the ocean. The path of the heavy precipitation, produced by storm centers moving eastward in the flow aloft, closely agreed with this channel in the sea level pressure and 700-mb. height anomaly charts.

Quite in contrast to these excessive amounts of rain, the Mississippi delta country was fast losing its battle with a prolonged drought of nearly 2 months. By the end of the first week in June, Jackson, Miss., had received only 0.13 inch of rain since the 21st of April [2]. Crop failure there was almost complete. Sources of drinking water were drying in southern Louisiana toward the end of the month. This subnormal rainfall was associated with abnormally high sea level pressures and above-normal heights and anticyclonic vorticity at 700 mb. (figs. 1 and

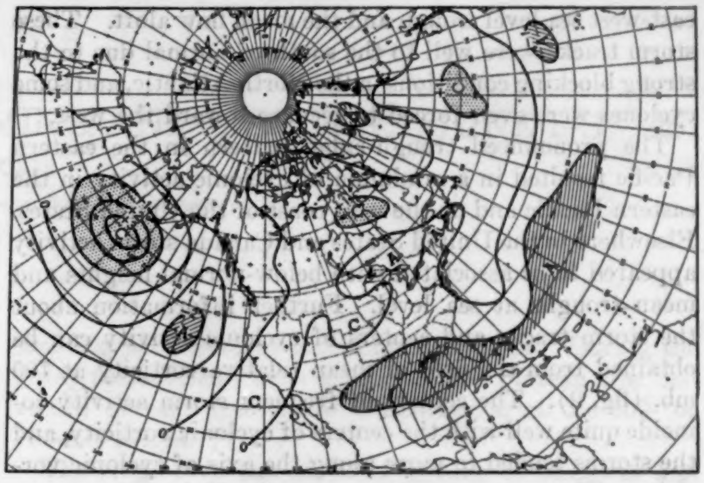


FIGURE 2.—Vertical component of mean relative geostrophic vorticity at 700 mb. for the 30-day period May 28–June 27, 1951, in units of 10^{-5} sec.$^{-1}$. Areas of cyclonic vorticity in excess of 1×10^{-5} sec.$^{-1}$ are dotted and labeled "C" at the center; areas of anticyclonic vorticity less than 1×10^{-5} sec.$^{-1}$ are hatched and labeled "A" at the center.

2). There was some slight and rather spotty relief from thunderstorms during the month. This temporary relief did help to bring up some of the late-planted cotton which had been retarded several weeks in dry soil. Another area of deficient rainfall was in the Southeast which was under the influence of ridge conditions at sea level and anticyclonic relative vorticity at 700 mb. Between these two areas of below-normal rainfall, there was an area in Alabama of heavy precipitation. This was mainly the result of squall line showers in the warm air occurring early in the month.

Above-normal temperatures generally prevailed east of the Mississippi. This warm weather was associated with a relatively flat 700-mb. ridge extending from the Lower Lakes region to the eastern Gulf of Mexico. The greatest positive temperature departures were found in the Southeast where positive 700-mb. height anomalies were located. In the Northeast, however, there was some blocking action as indicated by above-normal heights centered just north of the Great Lakes and negative height departures off the South Atlantic Coast. This latitudinal superposition of positive over negative anomalies appeared to be the westward extension of a much more pronounced blocking pattern over the Atlantic. This blocking action is also indicated on the sea level pressure anomaly chart. Thus with stronger northeasterly flow than normal, portions of the Northeast experienced temperatures which were below the June normals.

The region off the East coast was a seat of frequent cyclonic development during June as northeasterly flow relative to normal along the coast brought cool polar air into contact with warmer air over the Gulf Stream. This favorable field for cyclonic development and activity was reflected in the curvature of the isopleths on the sea level and 700-mb. charts. The cyclones from the mean trough off the coast moved across the Atlantic along the nearly

east-west sea level trough and the mean flow aloft. These storm tracks were well to the south of normal due to the strong blocking conditions in the North Atlantic, and some cyclones were even forced to recurve toward the west.

The pronounced trough-ridge pattern in the eastern Pacific resulted in a minimum of cyclonic activity in the eastern Pacific and on the west coast of the United States. Elsewhere in the United States and Canada storm activity appeared to be associated with below-normal heights and mean troughs at sea level. Further information about the storm tracks and centers of cyclonic activity can be obtained from the field of mean relative vorticity at 700 mb. (fig. 2). The centers of frequent storm activity coincide quite well with the centers of cyclonic vorticity, and the storms tended to move along the axis of cyclonic vorticity. The storms moving across the United States appeared to move freely in the westerly flow, whereas those along the central Canadian border showed a tendency toward motion in a more northerly direction around the anticyclonic vorticity center north of the Great Lakes.

The anticyclones during the month of June (Chart IX) occurred most abundantly in the regions under the influence of anticyclonic vorticity at 700 mb. Usually the Highs tended to move along the axis of anticyclonic vorticity and appeared to intensify in the centers. This was very pronounced in the Eastern Pacific. The anticyclone moving northwestward toward the Gulf of Alaska on the 27th increased its central pressure by 7 mb. in 48 hours. However some of the Highs during June moved directly across regions of cyclonic vorticity, as for example those moving through Montana. These were cold and relatively shallow Highs which tended to weaken rather rapidly as they moved through these regions. The central pressure of one of these on June 25 was reduced by 8 mb. in 24 hours.

In retrospect, we might think of the circulation and contrasting weather of June as a dress rehearsal for the disastrous weather to come in July. Toward the end of June over the Great Plains, the interaction between warm moist air from the south and cold dry air from the north continued unabated and even intensified. As June ended, a flood was already under way in Kansas and Missouri. During July this flood was to become one of the most destructive in the Nation's history.

REFERENCES

1. J. A. Carr, "Snow and Record Cold in Wyoming and Montana, June 1–3, 1951," *Monthly Weather Review*, vol. 79, No. 6, June 1951, pp. 129–132.
2. L. H. Clem, "The Weather and Circulation of May 1951," *Monthly Weather Review*, vol. 79, No. 5, May 1951, pp. 96–99.

SNOW AND RECORD COLD IN WYOMING AND MONTANA, JUNE 1–3, 1951

J. A. CARR

WBAN Analysis Center, U. S. Weather Bureau, Washington, D. C.

INTRODUCTION

Unusually low temperatures—accompanied by snow at some stations—occurred over Wyoming and Montana during the first 3 days of June. At many places the minima equalled or exceeded the lowest temperature ever recorded for the month. The cold weather was associated with a surface anticyclone which moved southwest out of Canada, through Montana, south and east into Wyoming, and then eastward across South Dakota. The drop in temperature was intensified by the adiabatic expansion of the air as it moved up-slope over the Plains and the eastern Rocky Mountains. The snowfall occurred principally over Wyoming where the up-slope motion was most intense.

CONDITIONS PRECEDING THE COLD WEATHER

During the last 2 days of May a center of low pressure, in an upper air trough over central Canada, moved northeast across the provinces of Saskatchewan and Manitoba. A continuation of the trough extended southwest from the Canadian Low to the Oregon coast. A large, warm ridge was increasing in strength some 200 to 300 miles west of the British Columbia and Washington State coastlines. The pattern produced by these two large features resulted in northerly winds over all of western Canada and eastern Alaska. Consequently, strong advection of cold air from the surface to the middle troposphere occurred southward over Canada and turned cyclonically as it approached the United States border near eastern Montana. Meanwhile, a low center developed over Oregon at the 700-mb. level on May 30, and moved east and southeast over Oregon and Idaho during the following 2 days.

CONDITIONS DURING THE COLD SPELL

Figure 1 shows the 700-mb. chart for June 1 at 1500 GMT, at which time the Low was centered over northwestern Colorado, and an off-shoot of the Pacific ridge had moved inland over southern British Columbia. These features controlled the circulation over the Plateau and the Pacific Coast States. The associated contour gradient at the 700-mb. level diverted part of the deep, broad flow of Polar air from Canada and directed it southwestward over Montana and Idaho, and thence south over Nevada. The cold air advection swept far to the south with below freezing temperatures over central Arizona. During the 3-day period, many raob stations in the Plateau area had record or near record low temperatures at the 500- or 700-mb. heights [1].

The ridge over the northern border of Montana and the trough running southwestward from the low center in the United States were jointly responsible for the cold air invasion over the Plateau. Without the appended trough, the ridge and low center aloft could have been expected to deflect the air flow to the east and southeast along the east side of the Divide. Such a flow would have moved the cold tongue east from the Plateau region and on to the Plains, during the course of the next 2 days, as the low center moved to the northeast.

The chart for June 2 at 1500 GMT (fig. 2), shows the cold tongue had remained over the Plateau as the Low moved rapidly northeastward to near Fargo, N. Dak. As can be seen, the trough on the southwest side of the Low and the ridge to the northwest caused cold northeast winds

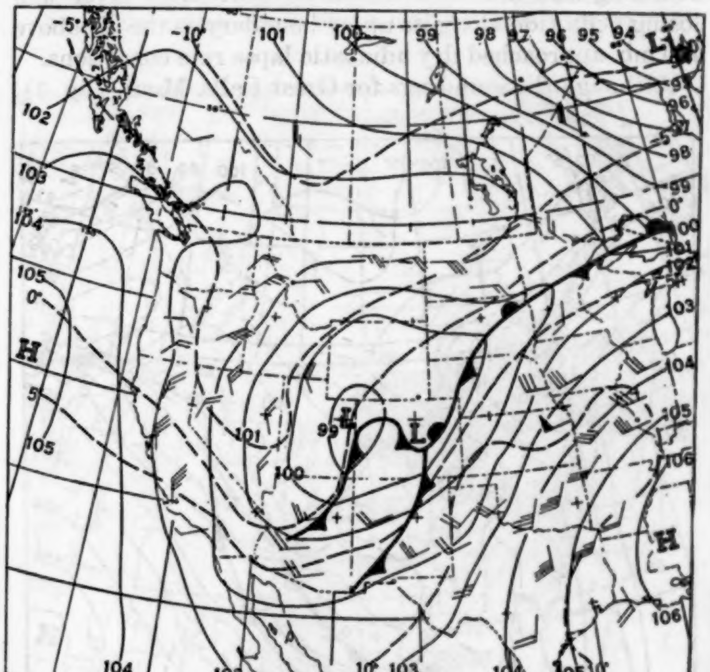


FIGURE 1.—700-mb. chart for 1500 GMT, June 1, 1951. Contours (solid lines) at 100-foot intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are at intervals of 5° C. Barbs on wind shafts are for speeds in knots (pennant=50 knots, full barb=10 knots, and half barb=5 knots).

of considerable depth to flow southwestward over Montana and into Colorado and Utah.

Winds at the 700-mb. surface shifted to a more westerly direction during the next 24 hours as the heights rose over the Plateau and the Western Plains. Figure 3 illustrates the new pattern on June 3 at 1500 GMT, showing clearly the advance of the cold tongue—now east of the Divide—with freezing temperatures as far south as the New Mexico-Colorado border. Over western Montana the trend toward rising temperatures had already set in. In the next 24 hours, the cold tongue moved east and the freezing isotherm retreated to the latitude of North Platte, Nebr. Over the Plateau the temperatures rose as the air came from the south and southwest.

During the 3-day period the temperature over Montana, Wyoming, and Colorado remained almost consistently cold at the 700-mb. level with readings of −5° to −10° C.

The soundings at Rapid City, S. Dak., (fig. 4), were selected to represent the vertical structure of the Polar air in the lower and middle troposphere. Ascents on June 1 and June 2 indicated cooling and increasing depth of the turbulent layer from the surface to near the 700-mb. level. The depth of this layer of steep lapse rate permitted only small daytime increases in surface temperatures. Although the cooling was less pronounced above 700 mb., the two curves show that it extended well up into the troposphere. The curve for June 3 shows warming from the surface up to near 700 mb., but cooling from this level to 400 mb., especially being 700 and 500 mb. The latter sounding also indicated the surface turbulent layer was losing definition along its upper boundary as the air above 700 mb. approached dry adiabatic lapse rate conditions.

Although the soundings for Great Falls, Mont. (fig. 5), were in the same air mass as those for Rapid City, they show interesting differences. Comparing the soundings for June 1 and 2 it can readily be seen that the air became warmer between the surface and 700 mb. at Great Falls. Then it alternately cooled and warmed from the 700- to 500-mb. level. Over the remaining 150 mb. the temperatures remained about the same. From June 2 to 3, warming took place from the surface upward to near 600 mb., but the layer above 600 mb. cooled, with the result that the lapse rate of the entire column of air approached the dry adiabatic lapse rate.

Investigation as to the cause, or causes, of this warming near the surface was carried out by tracing the trajectory of the air. A cursory examination of the surface maps would indicate that the air had moved up-slope over Montana with consequent cooling. However, an air parcel located just northwest of Aberdeen, S. Dak., on June 1, was traced along a path that led to Rapid City. During the travel the air moved 2,000 feet uphill and cooled 10° F. From Rapid City, the air streamed west and uphill through eastern Wyoming. When about half way between the eastern border of Wyoming and the Divide, it curved slowly clockwise and moved northwestward in the vicinity of Cody, Wyo. Shortly after leaving Cody, the air reached its highest point where the ground elevation reached 9,000 feet, on the Montana-Wyoming border. The parcel which had had a temperature of 36° F. was now down to 31°. During the next 12 hours the air underwent adiabatic compression as it descended 5,400 feet to a point near Livingston, Mont., at which place the temperature read 45° F. After another 24 hours of downhill travel the air parcel was traced to the area west of Glasgow, Mont., with a temperature of 69° F.

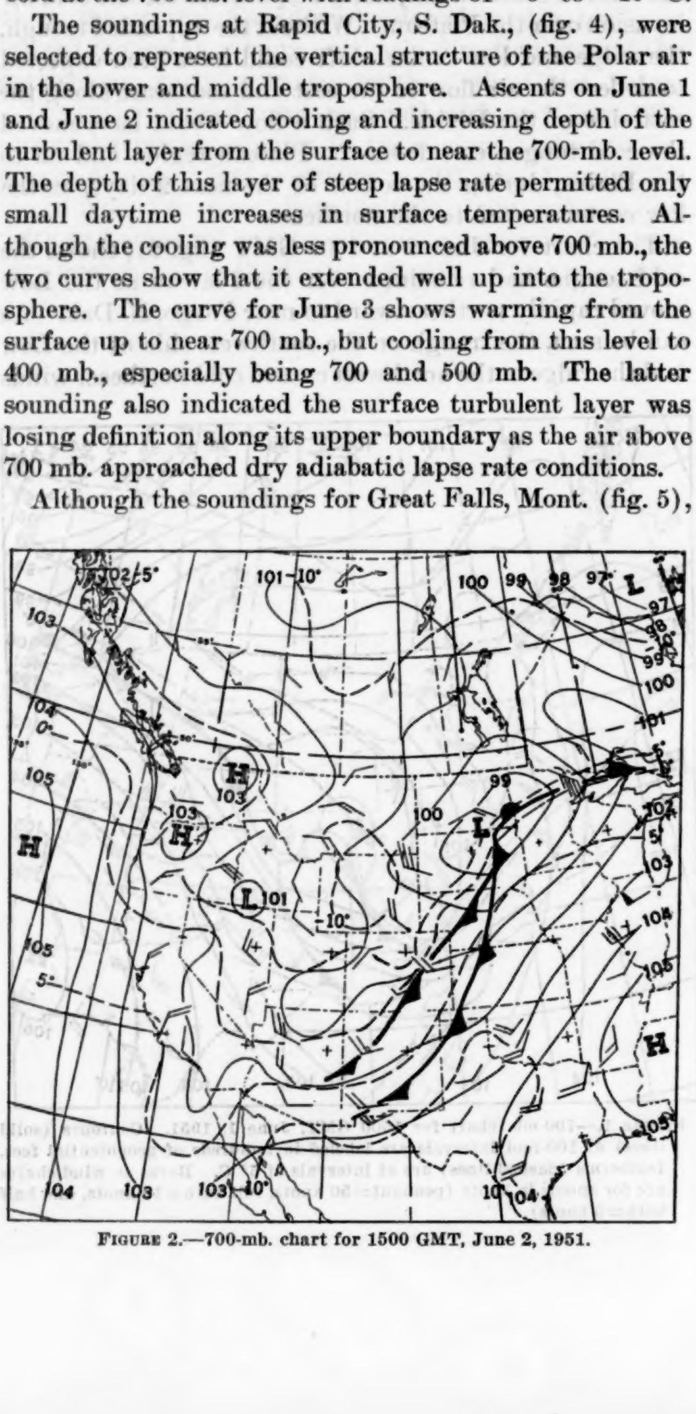


FIGURE 2.—700-mb. chart for 1500 GMT, June 2, 1951.

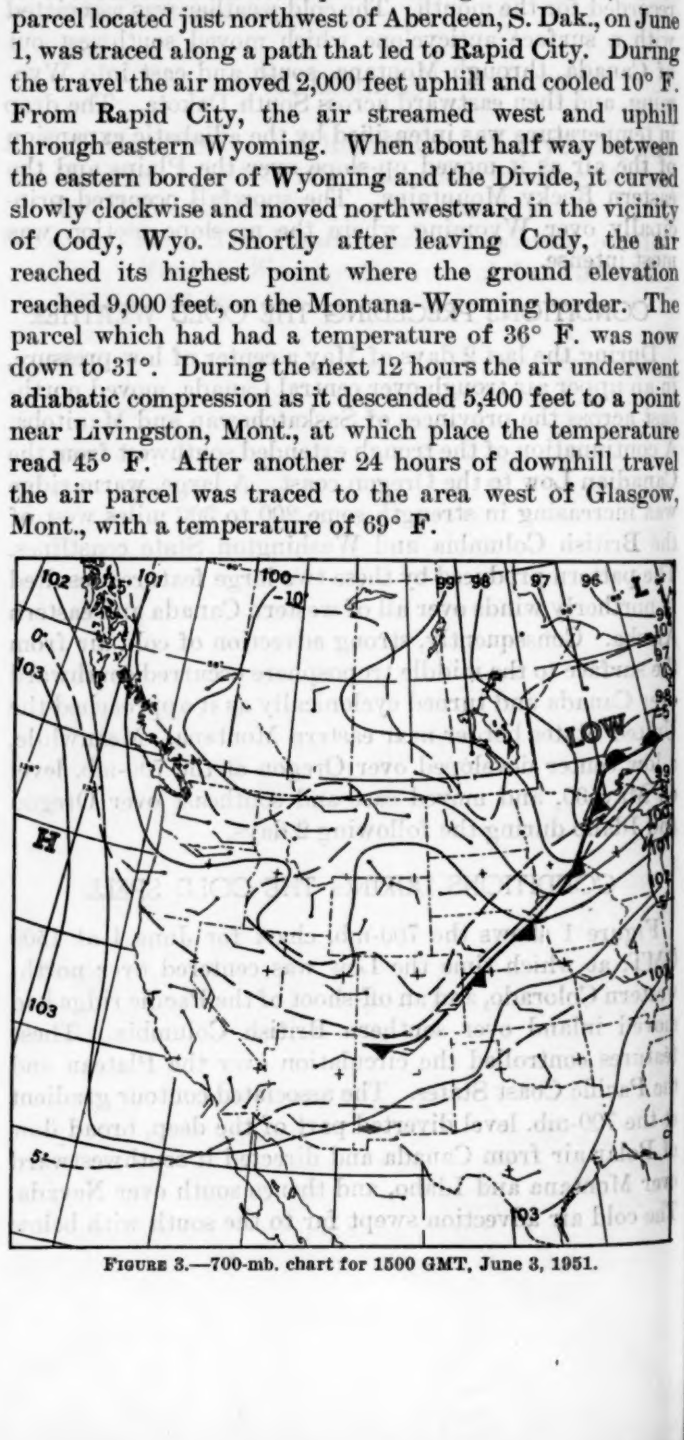


FIGURE 3.—700-mb. chart for 1500 GMT, June 3, 1951.

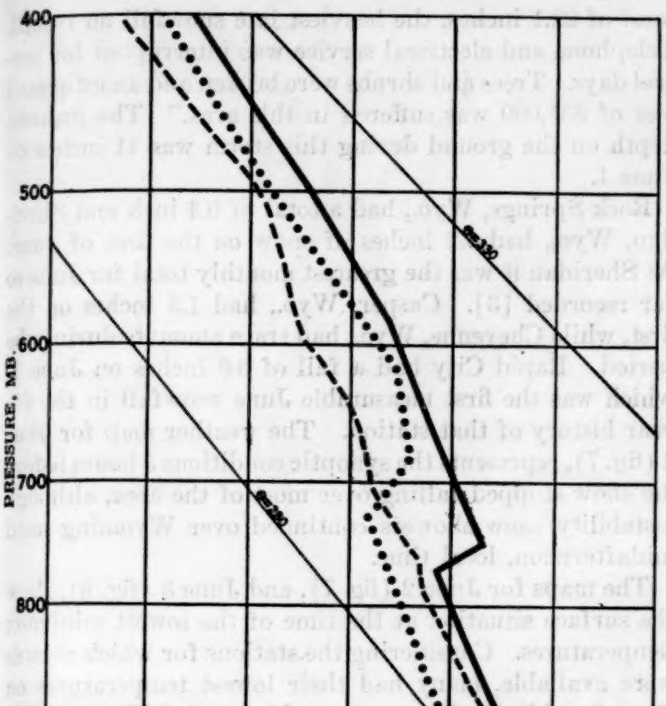


FIGURE 4.—Upper air sounding—Rapid City, S. Dak., at 0300 GMT, on June 1 (solid line), June 2 (dotted line), and June 3 (dashed line).

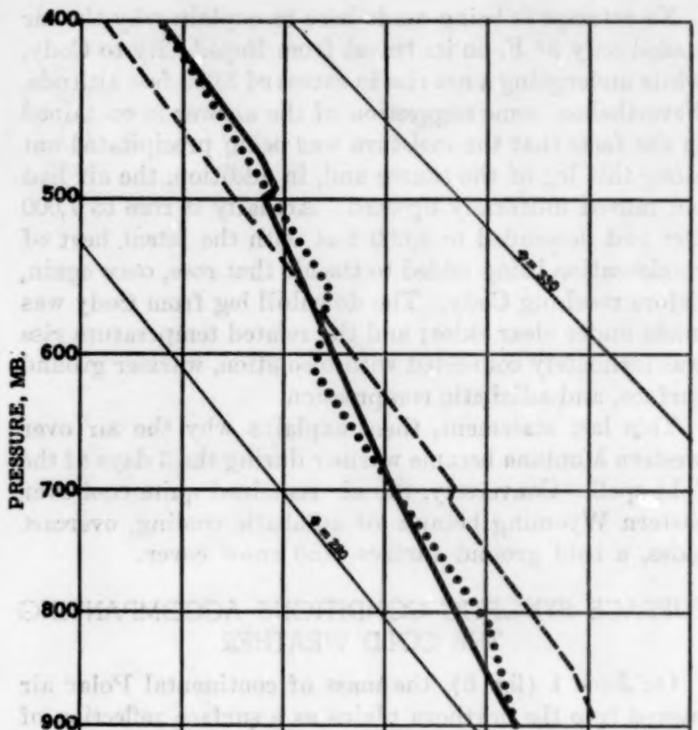


FIGURE 5.—Upper air soundings—Great Falls, Montana, at 0300 GMT, on June 1 (solid line), June 2 (dotted line), and June 3 (dashed line).

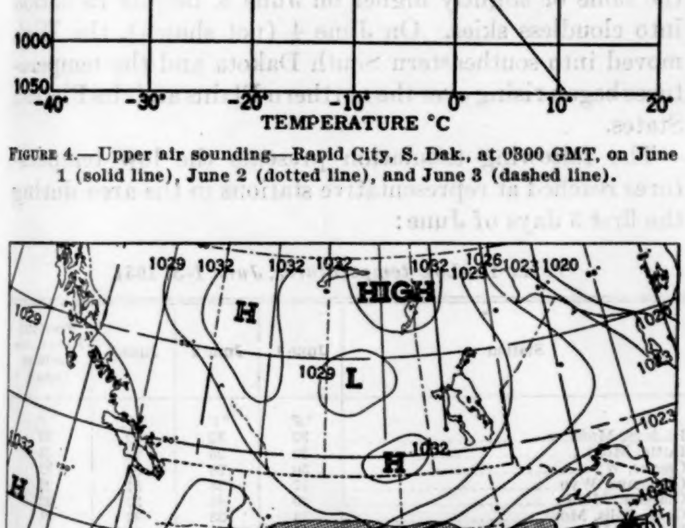


FIGURE 6.—Surface weather chart for 1230 GMT, June 1, 1951. Shading indicates areas of active precipitation.

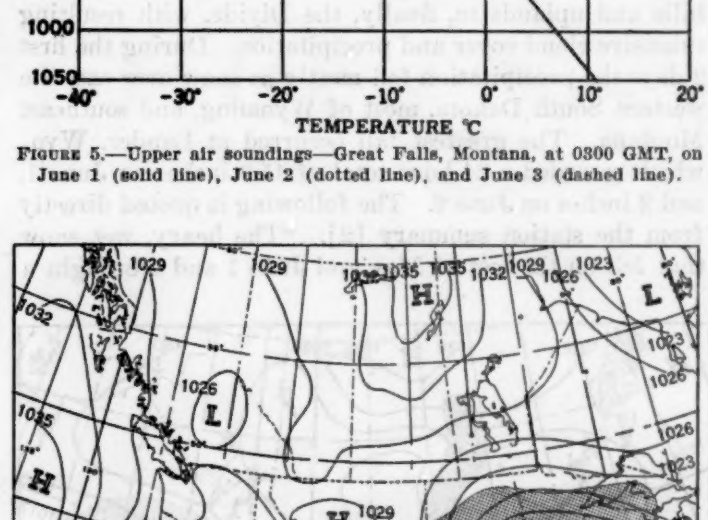


FIGURE 7.—Surface weather chart for 1230 GMT, June 2, 1951.

960514—51——3

No attempt is being made here to explain why the air cooled only 5° F. on its travel from Rapid City to Cody, while undergoing a net rise in excess of 3,000 feet altitude. Nevertheless, some suggestion of the answer is contained in the facts that the moisture was being precipitated out along this leg of the course and, in addition, the air had not moved uniformly upward. Actually it rose to 7,000 feet and descended to 5,000 feet with the latent heat of condensation being added to the air that rose, once again, before reaching Cody. The downhill leg from Cody was made under clear skies; and the related temperature rise was intimately connected with insolation, warmer ground surface, and adiabatic compression.

This last statement, then, explains why the air over western Montana became warmer during the 3 days of the cold spell. Conversely, the air remained quite cool over eastern Wyoming because of adiabatic cooling, overcast skies, a cold ground surface, and snow cover.

SURFACE SYNOPTIC CONDITIONS ACCOMPANYING THE COLD WEATHER

On June 1 (fig. 6), the mass of continental Polar air moved into the northern plains as a surface reflection of the circulation at higher levels. The anticyclonic circulation moved air across the plains and up-slope over the foothills and uplands to, finally, the Divide, with resulting extensive cloud cover and precipitation. During the first 2 days the precipitation fell mostly as snow over extreme western South Dakota, most of Wyoming, and southeast Montana. The greatest fall occurred at Lander, Wyo., which recorded a 24-hour total of 15.9 inches on June 1, and 2 inches on June 2. The following is quoted directly from the station summary [2]. "The heavy, wet snow that fell on the last of May and June 1 and 2 brought a total of 22.1 inches, the heaviest late snowfall on record. Telephone and electrical service was interrupted for several days. Trees and shrubs were broken and an estimated loss of $35,000 was suffered in this area." The greatest depth on the ground during this storm was 11 inches on June 1.

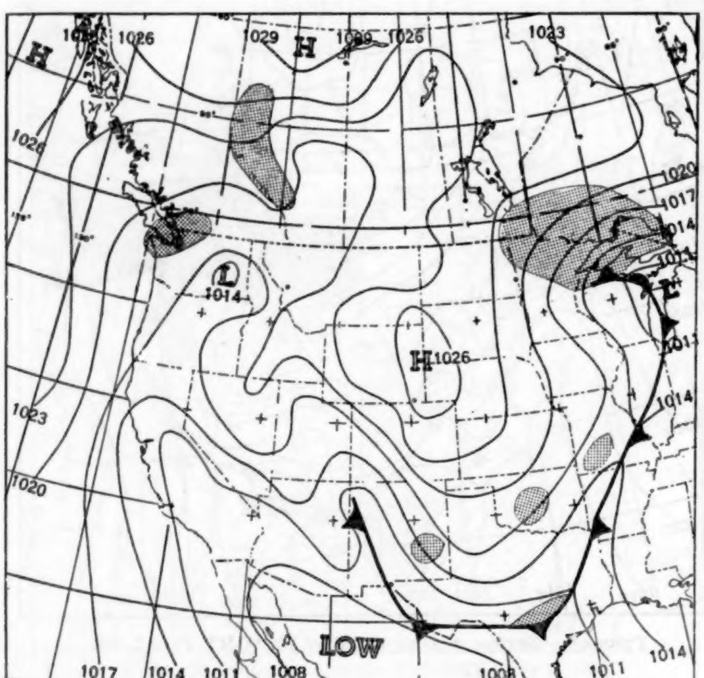


FIGURE 8.—Surface weather chart for 1230 GMT, June 3, 1951.

Rock Springs, Wyo., had a total of 0.4 inch and Sheridan, Wyo., had 3.2 inches of snow on the first of June. At Sheridan it was the greatest monthly total for June so far recorded [3]. Casper, Wyo., had 1.5 inches on the first, while Cheyenne, Wyo., had trace amounts during the period. Rapid City had a fall of 3.6 inches on June 1, which was the first measurable June snowfall in the 63-year history of that station. The weather map for June 2 (fig. 7), represents the synoptic conditions 3 hours before the snow stopped falling over most of the area, although instability snow showers continued over Wyoming until midafternoon, local time.

The maps for June 2 (fig. 7), and June 3 (fig. 8), show the surface situation at the time of the lowest minimum temperatures. Considering the stations for which records were available, many had their lowest temperatures on June 2, while under overcast skies and falling rain or snow. The minimum temperatures at many stations were the same or slightly higher on June 3, despite radiation into cloudless skies. On June 4 (not shown), the High moved into southeastern South Dakota and the temperatures began rising over the northern Plains and the Plateau States.

The following tabulation presents the low temperatures reached at representative stations in the area during the first 3 days of June:

TABLE 1.—*Low temperatures, June 1–3, 1951*

Station	June 1	June 2	June 3	Previous June minimum of record
	°F.	°F.	°F.	°F.
Billings, Mont	32	32	32	32
Butte, Mont	30	25	24	23
Casper, Wyo	30	28	30	32
Cheyenne, Wyo	27	25	31	28
Glasgow, Mont	30	43	37	32
Great Falls, Mont	34	33	42	31
Helena, Mont	34	34	31	31
Kalispell, Mont	28	30	38	31
Lander, Wyo	29	27	25	26
Missoula, Mont	31	31	35	30
Rapid City, S. Dak	31	31	33	32
Rock Springs, Wyo	28	26	26	27
Sheridan, Wyo	32	30	27	29

In addition, Goodland, Kans., had a new record low for June of 31° on June 2—the previous low having been 36°.

REFERENCES

1. U. S. Weather Bureau, "Extreme Temperatures in the Upper Air", *Technical Paper No. 3*, Washington, D. C., July 1947.
2. U. S. Weather Bureau, *Station Meteorological Summary*, Lander, Wyoming, June 1951 (W. B. Form 1001-C).
3. U. S. Weather Bureau, *Local Climatological Summary with Comparative Data, 1950* (for individual stations).

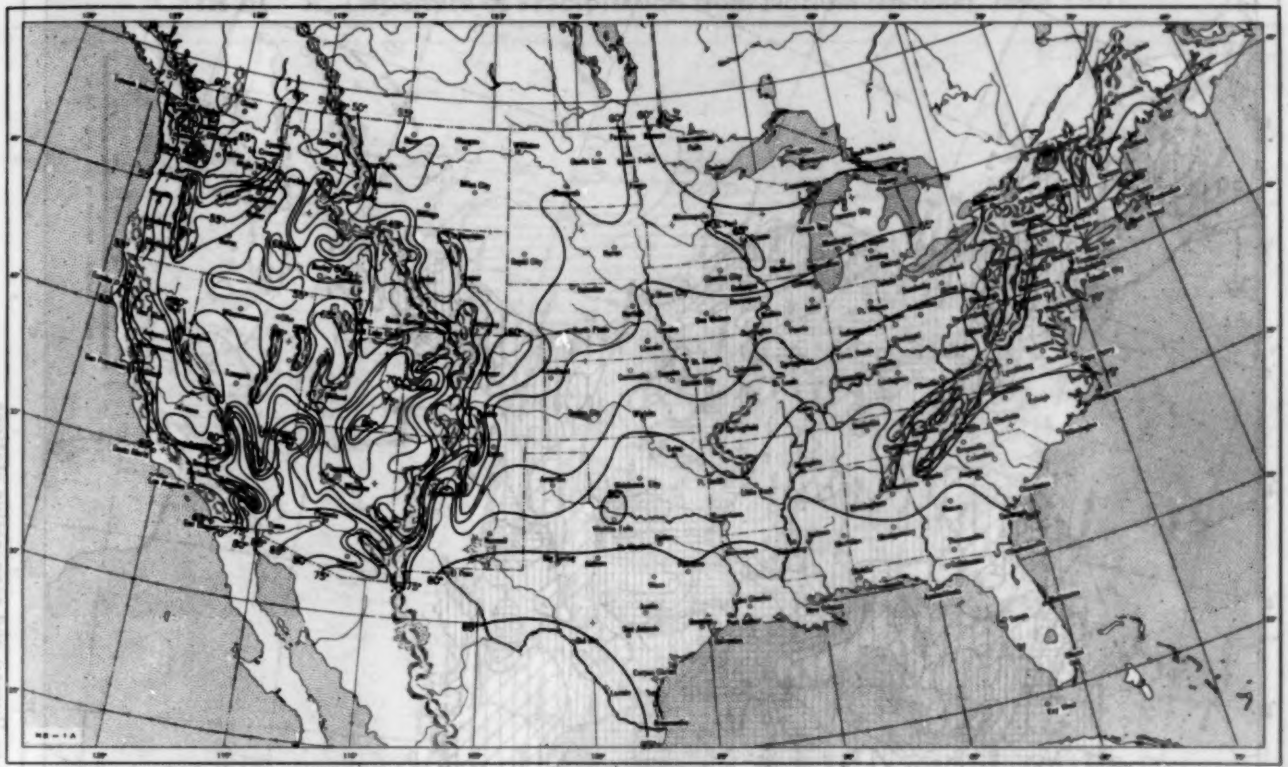
U. S. GOVERNMENT PRINTING OFFICE: 1951

[illegible]

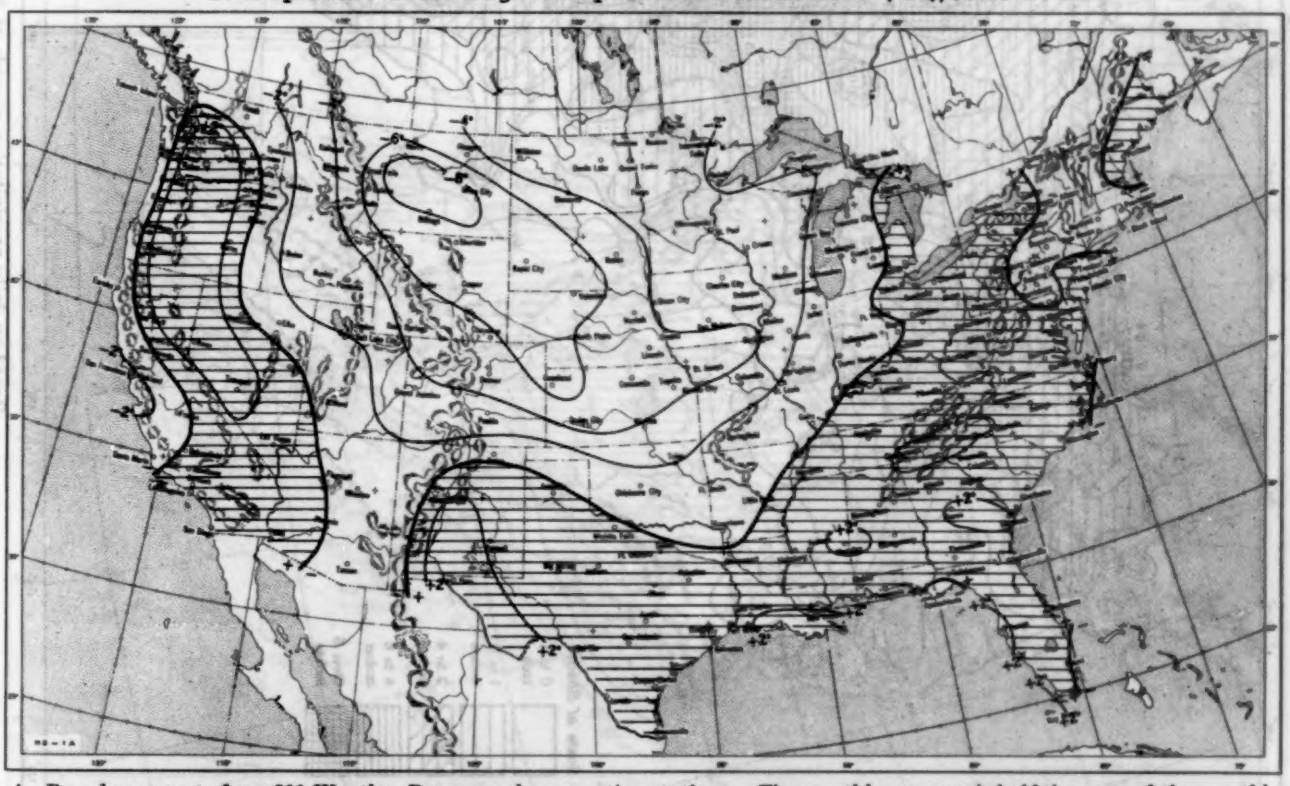
[illegible]

[illegible]

Chart I. A. Average Temperature (°F.) at Surface, June 1951.

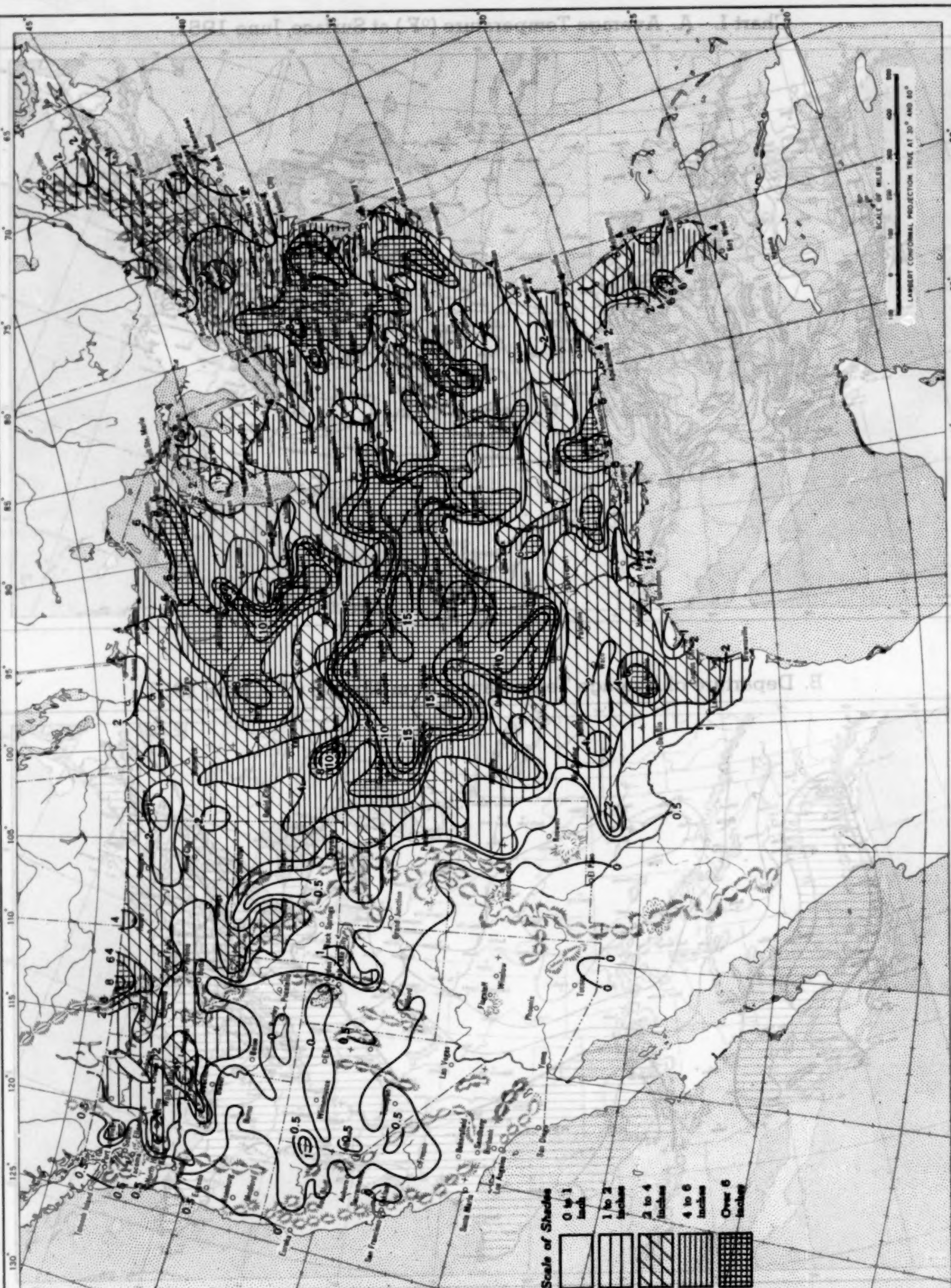


B. Departure of Average Temperature from Normal (°F.), June 1951.



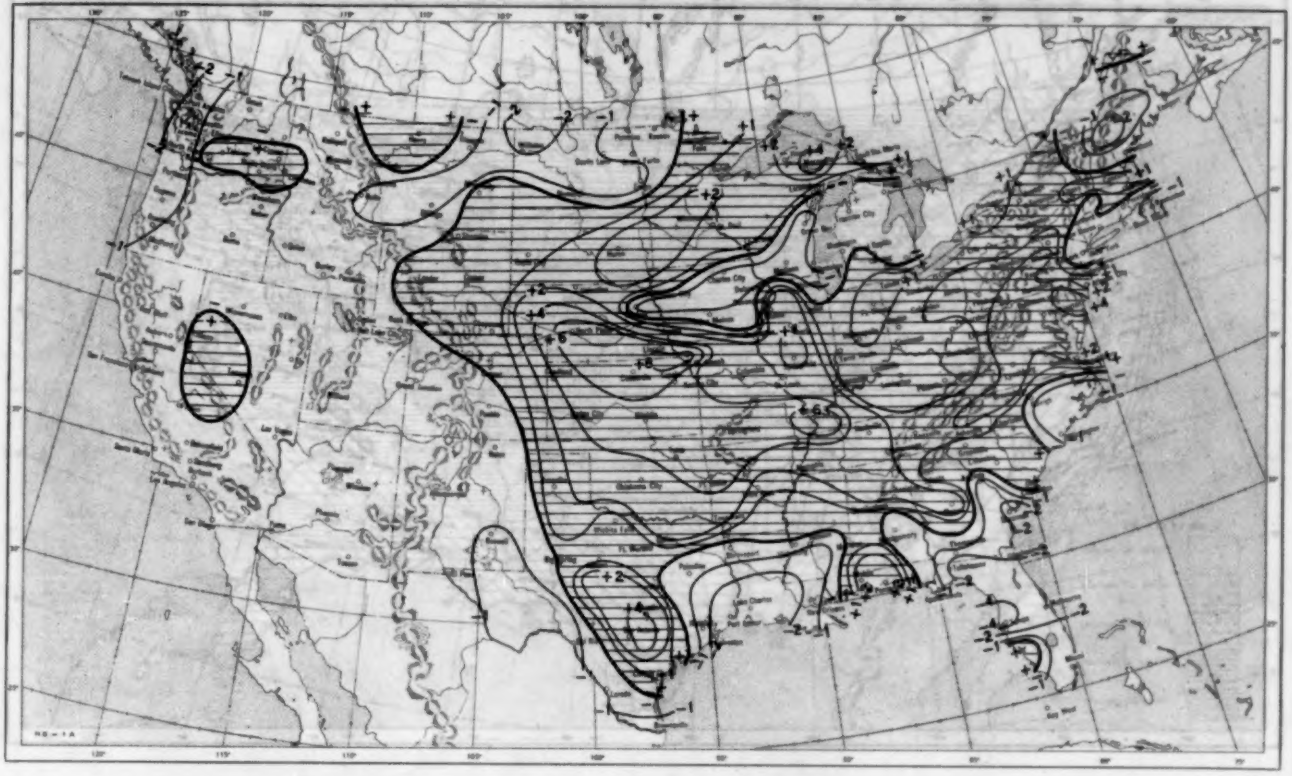
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), June 1951.

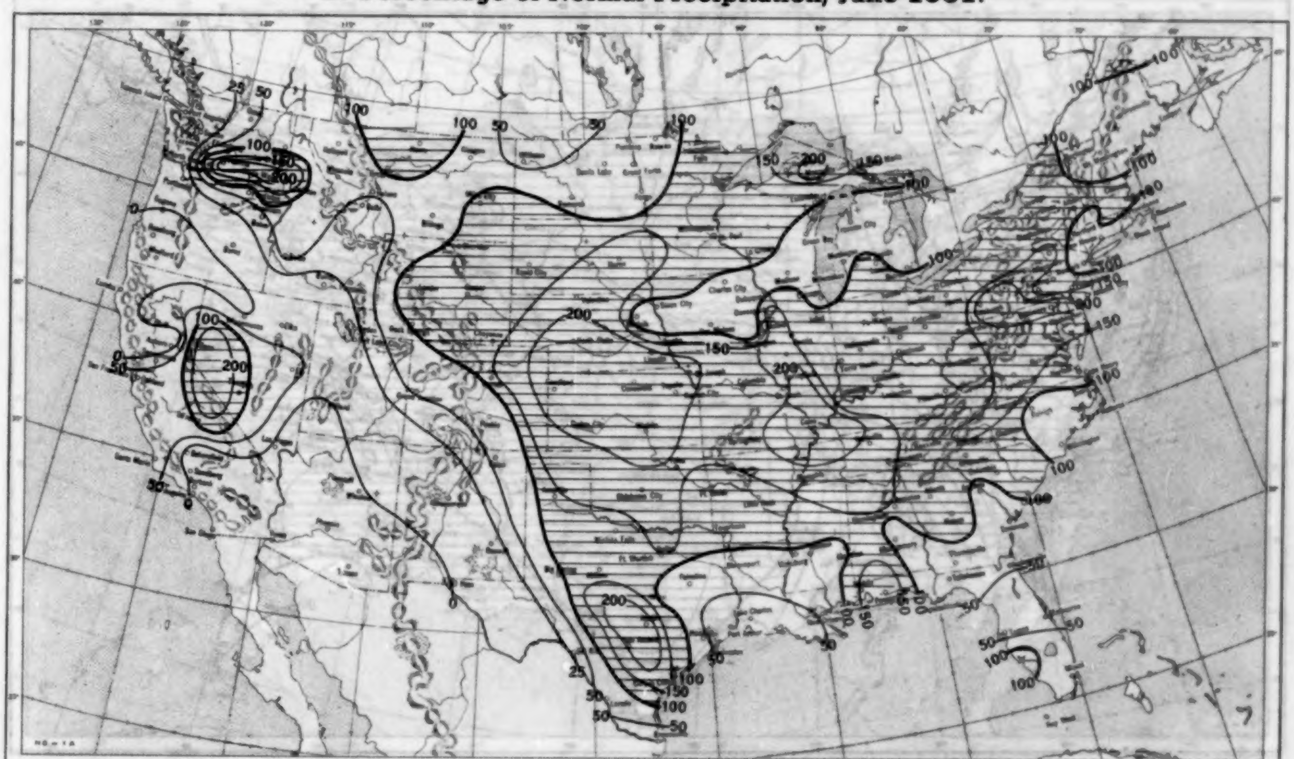


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), June 1951.

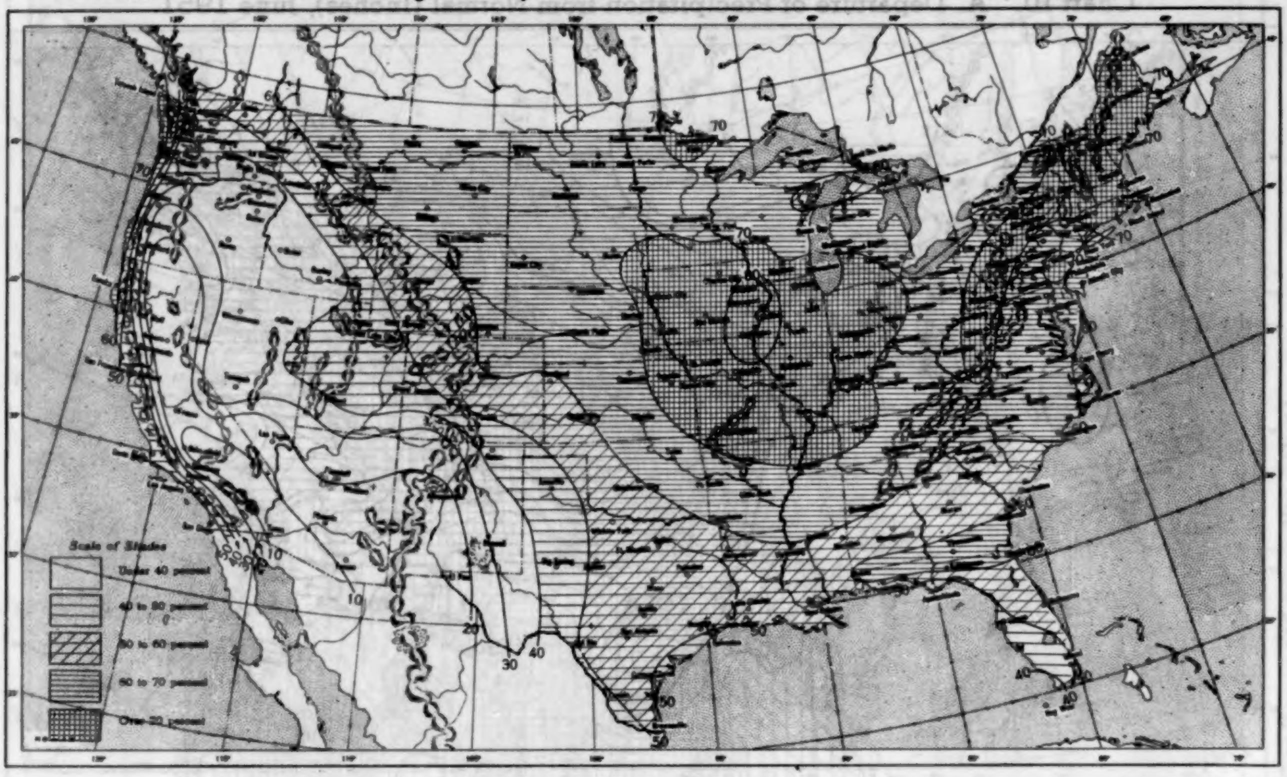


B. Percentage of Normal Precipitation, June 1951.

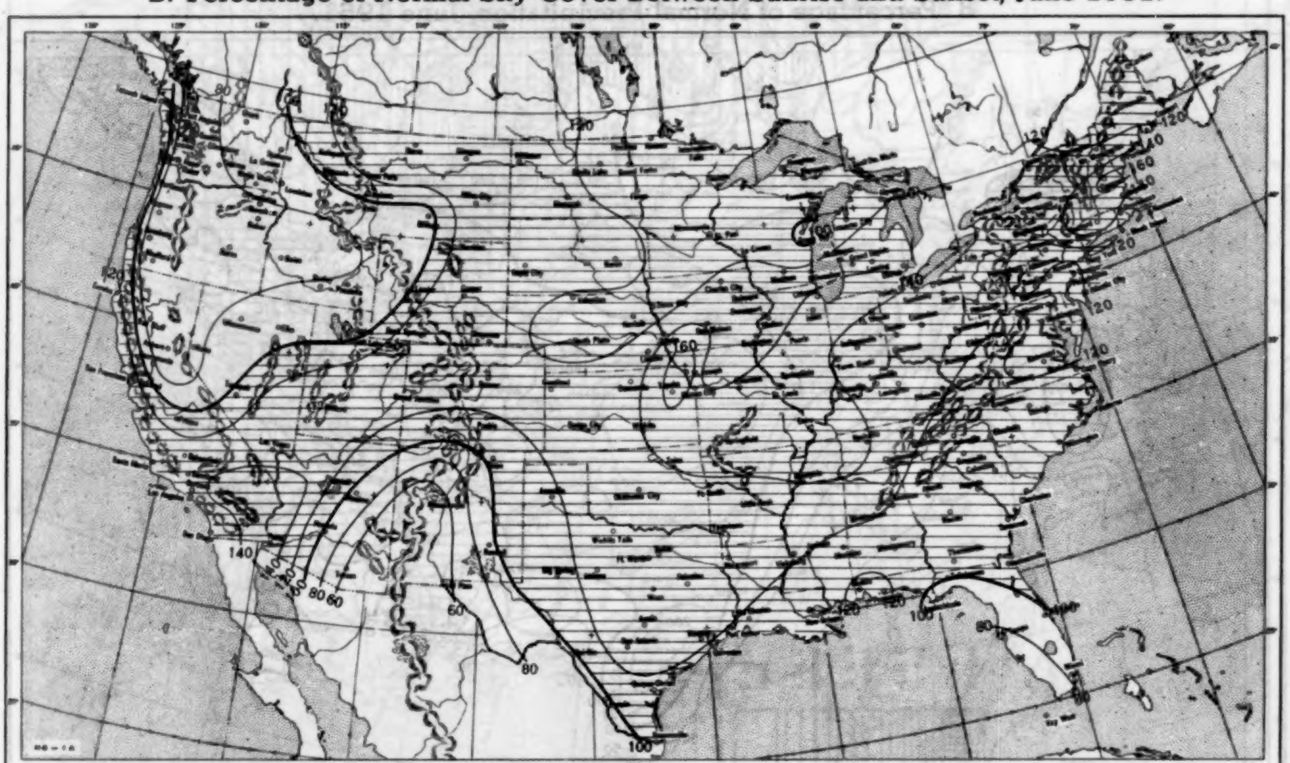


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, June 1951.

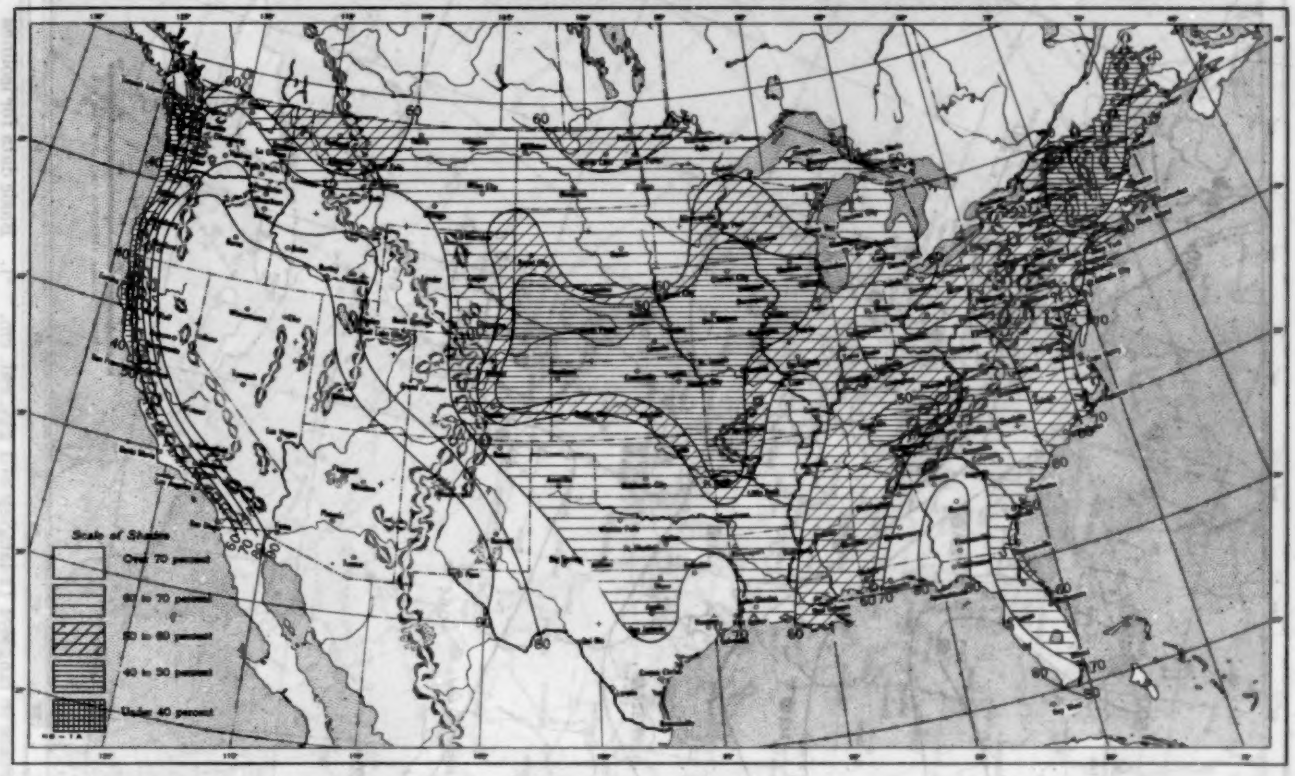


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, June 1951.

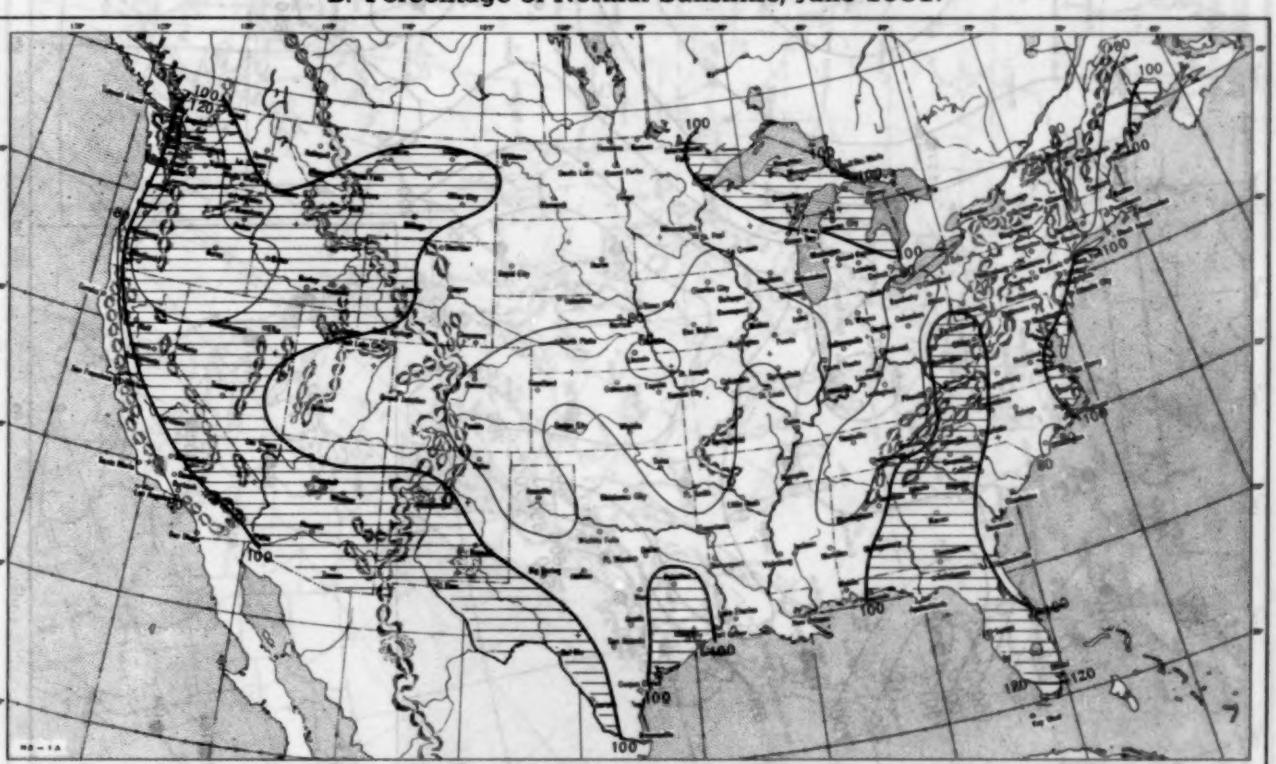


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, June 1951.



B. Percentage of Normal Sunshine, June 1951.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, June 1951. Inset: Percentage of Normal Average Daily Solar Radiation, June 1951.

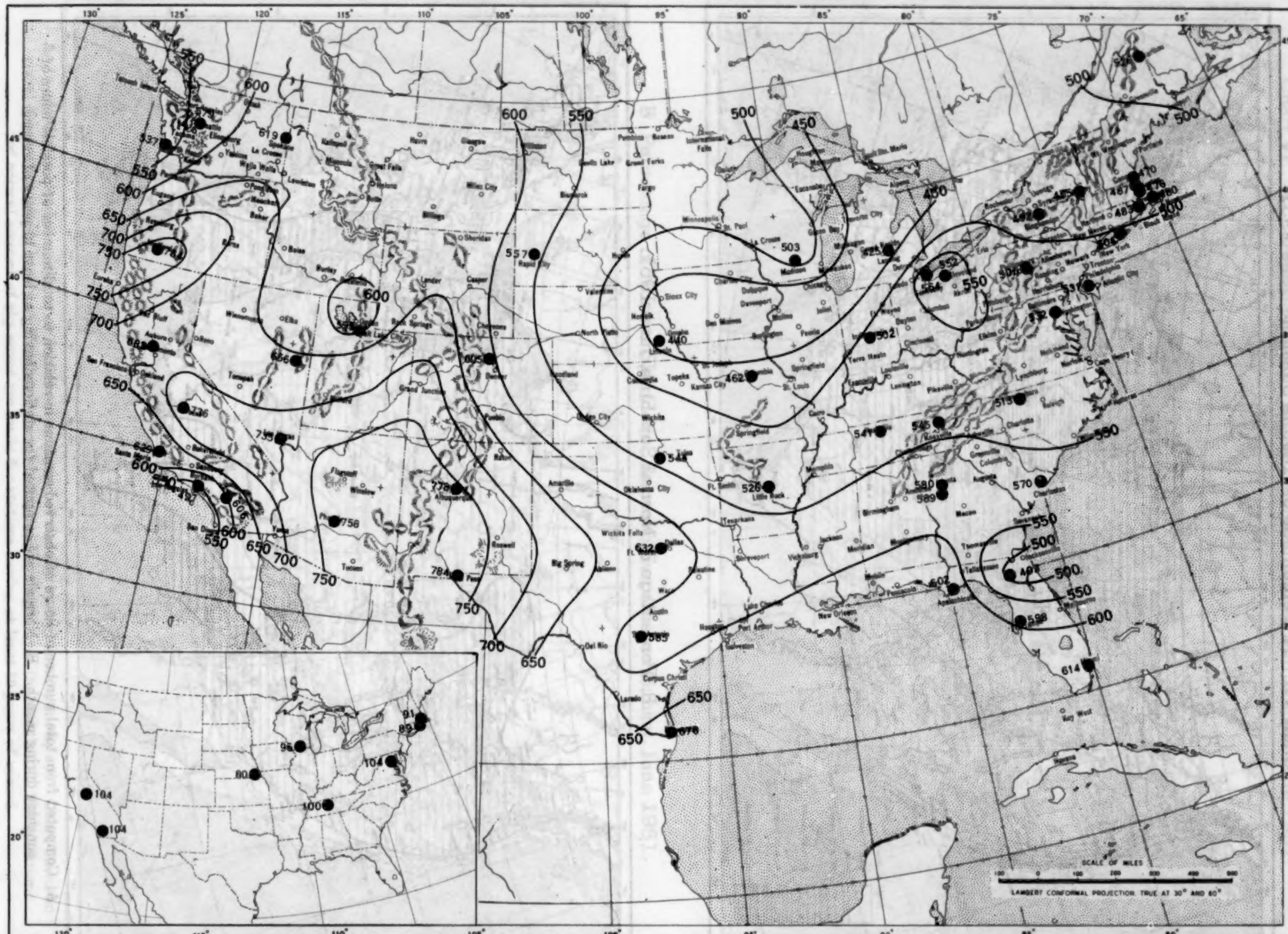
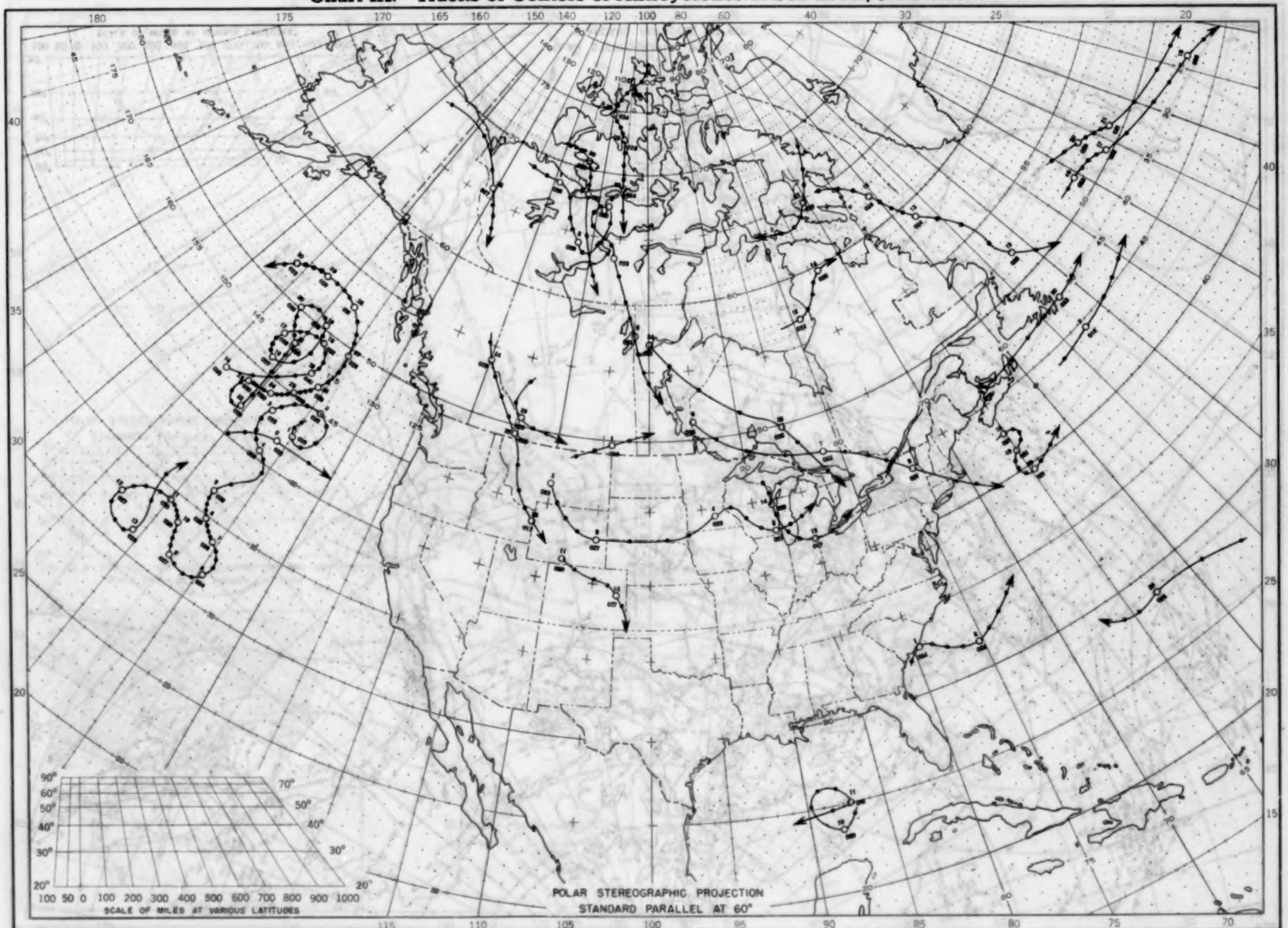


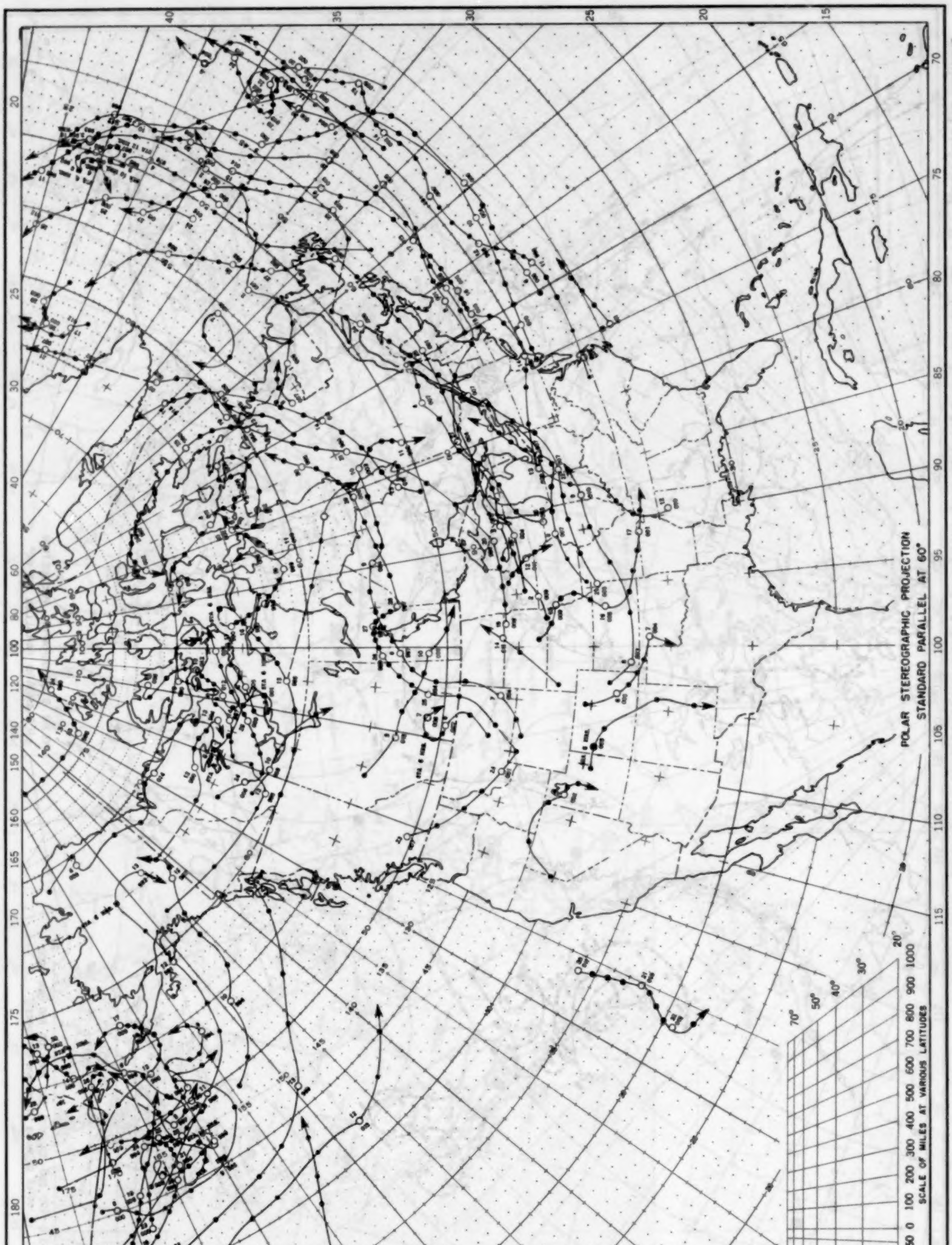
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, June 1951



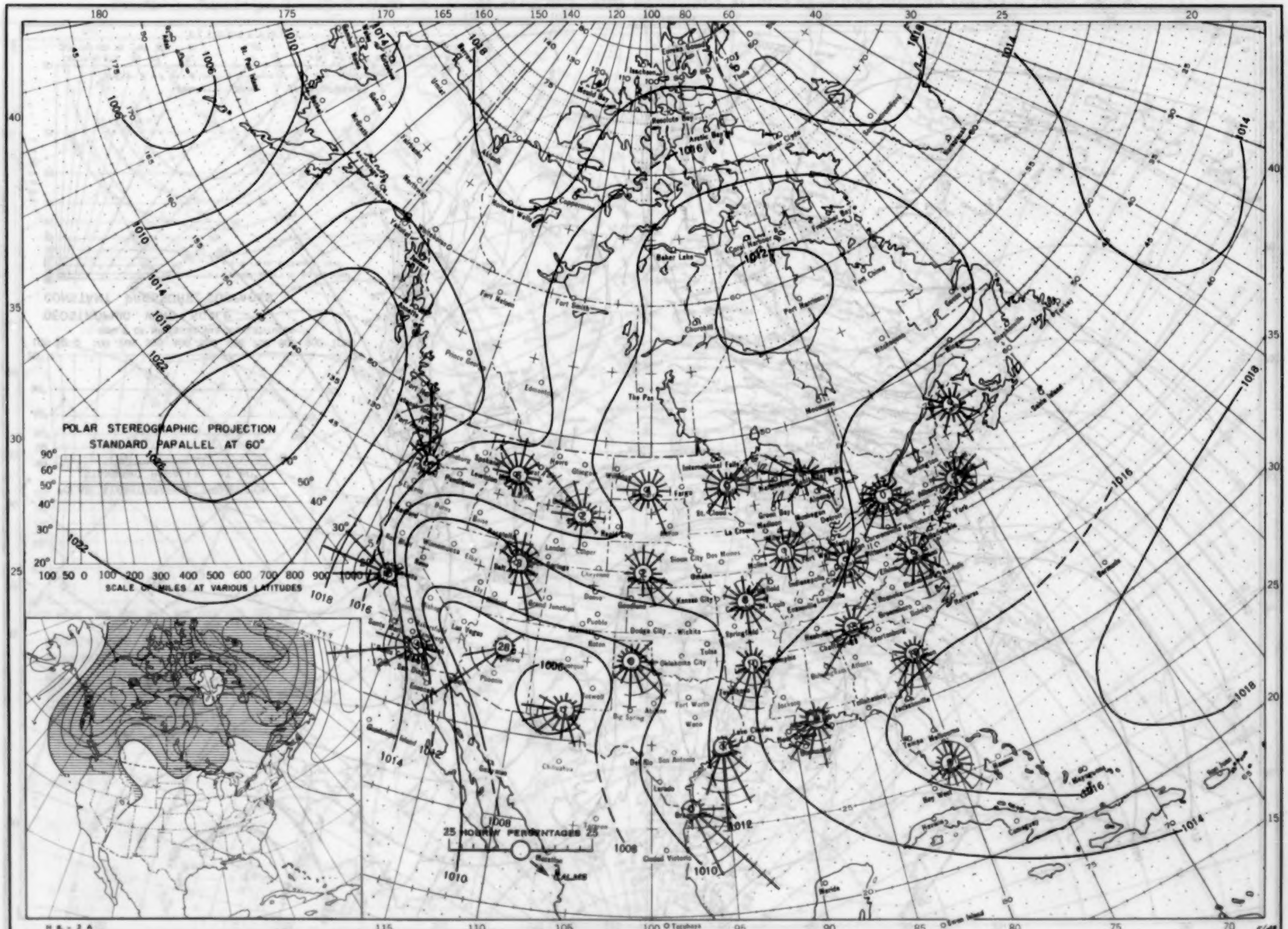
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, June 1951.



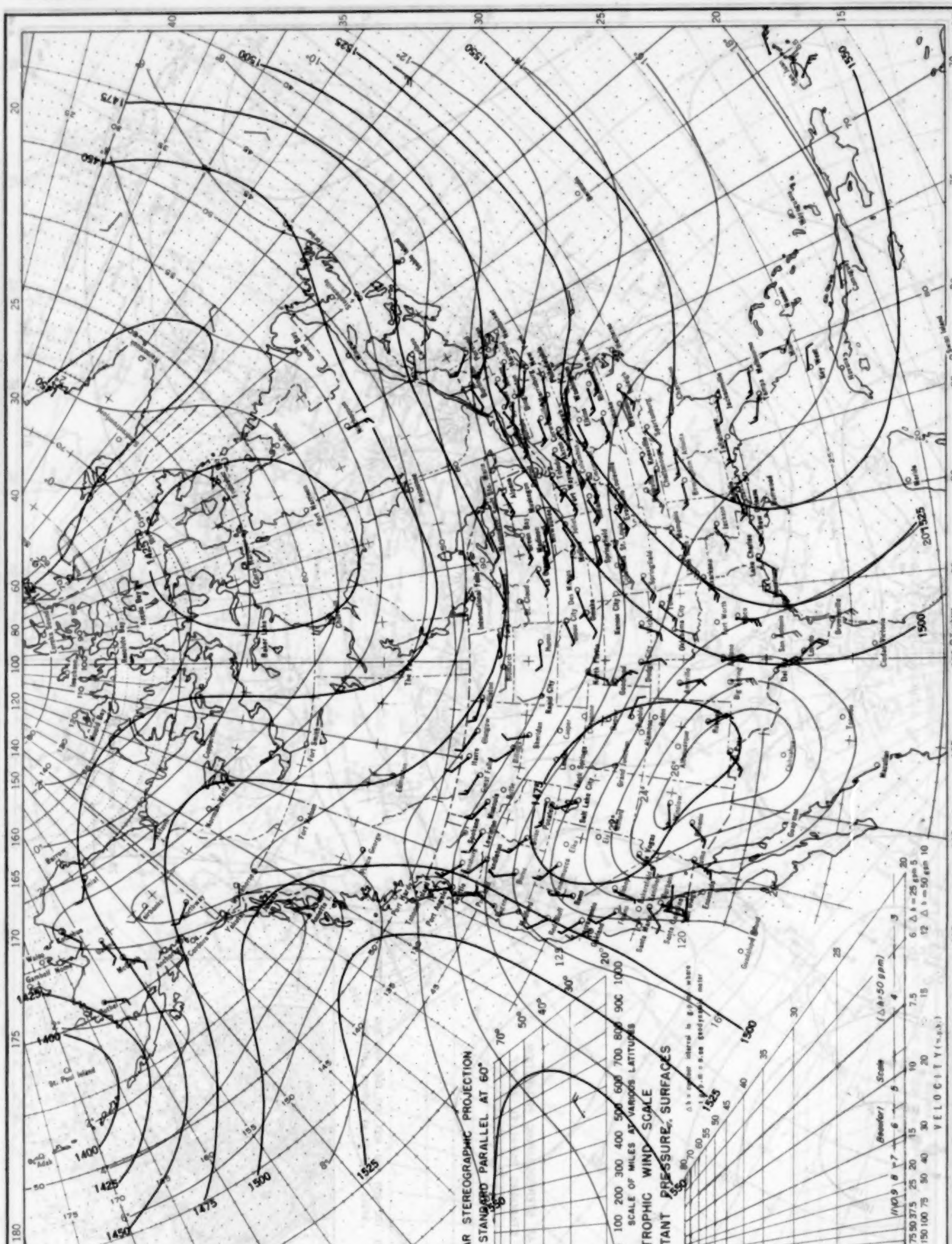
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, June 1951. Inset: Departure of Average Pressure (mb.) from Normal, June 1951.



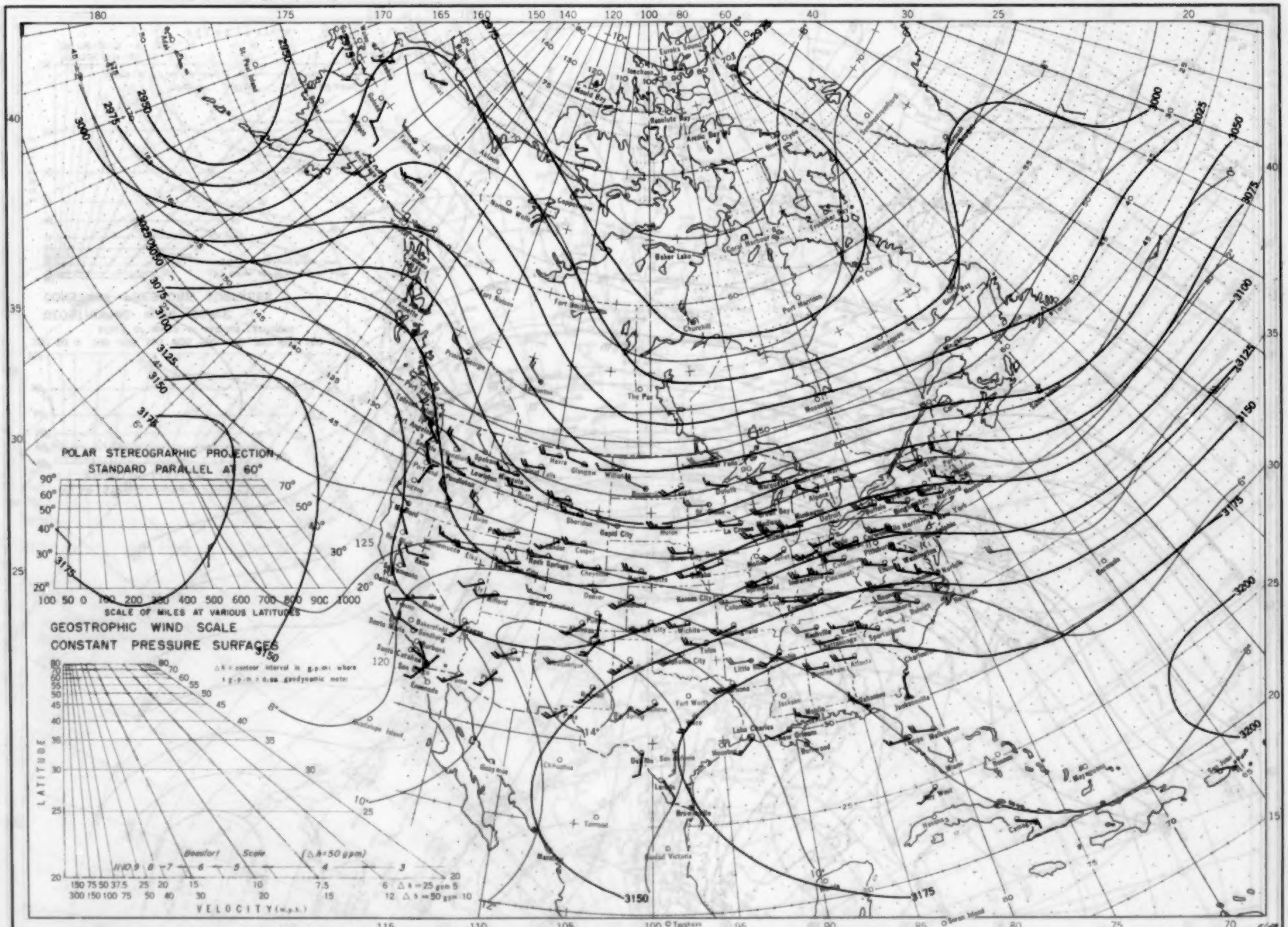
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), June 1951.



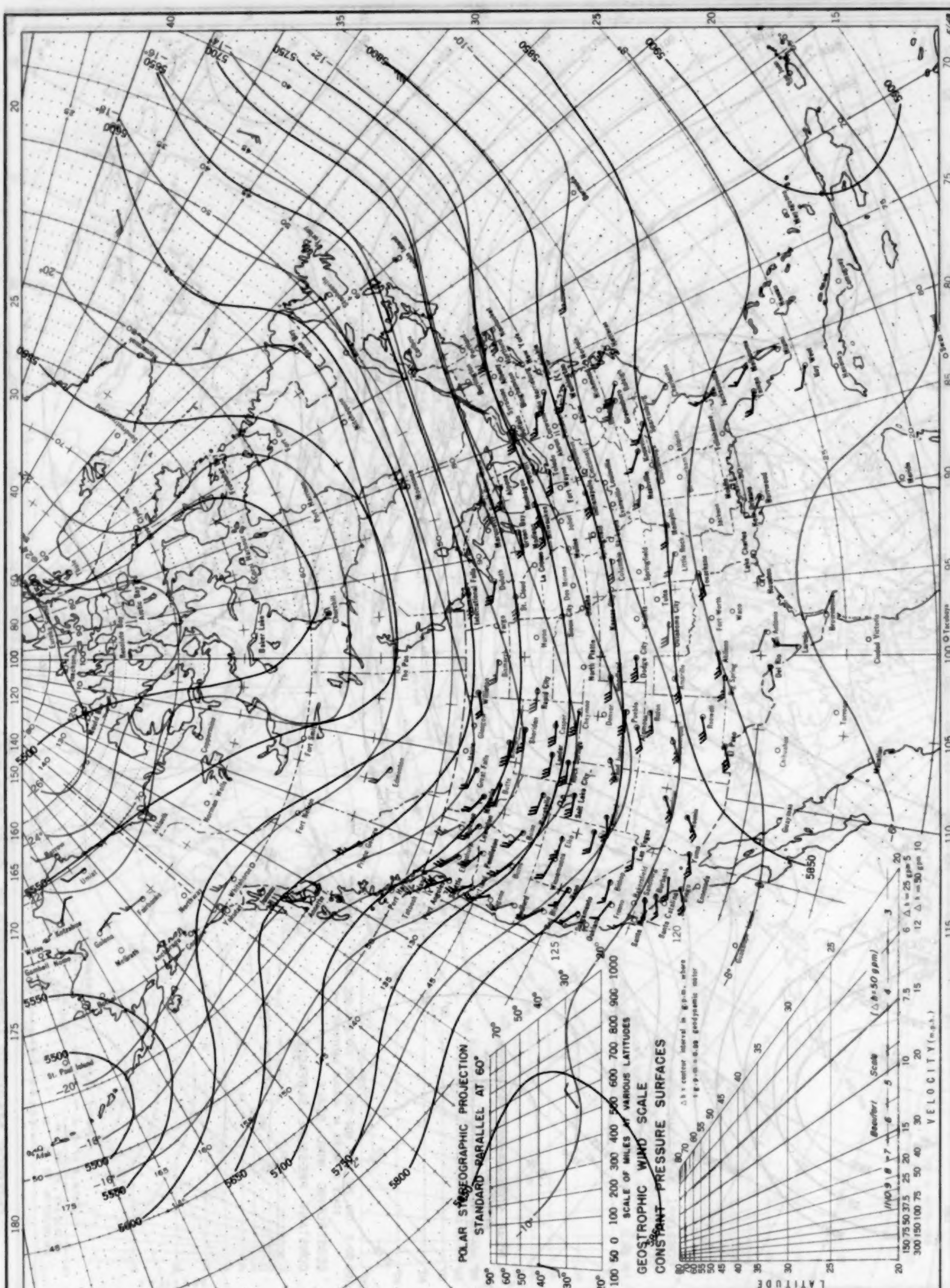
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), June 1951.



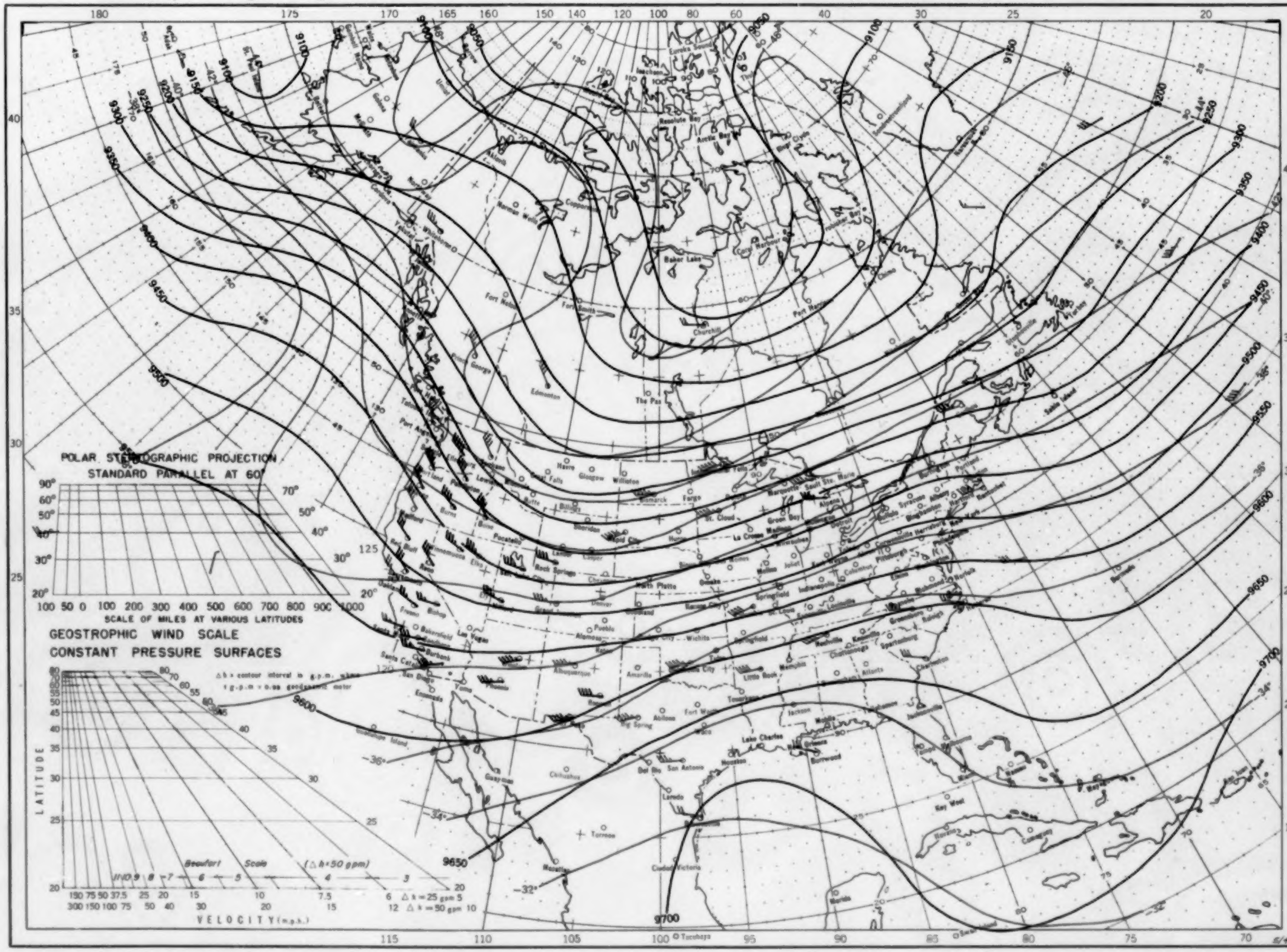
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), June 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), June 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.